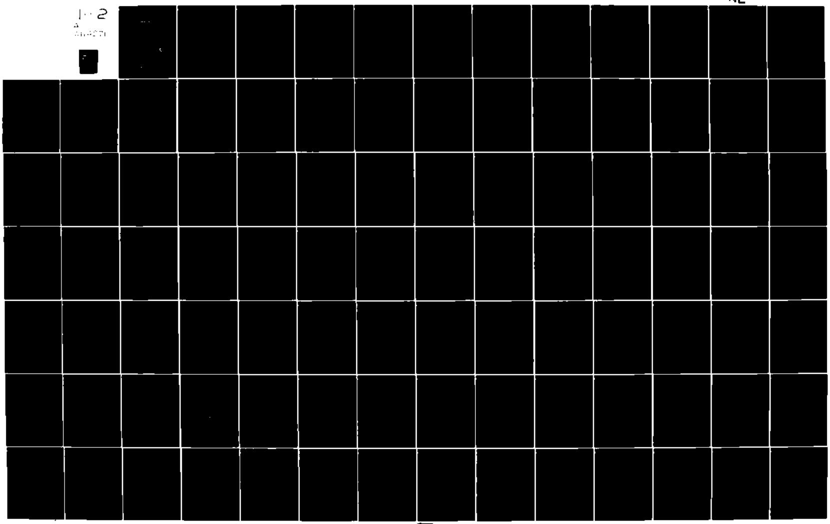
AD-A114 271 SYSTEMS CONTROL TECHNOLOGY INC WEST PALM BEACH FL F/G 1/4
AVIONICS CERTIFICATION REQUIREMENTS AND PROCEDURES ERROR BUDGFT--ETC(U)
DEC 81 R J ADAMS DTFA01-80-4-10581
UNCLASSIFIED FAA/RD-81-107 NL



DOT/FAA/RD-81/107

Systems Research &
Development Service
Washington, D.C. 20590

Avionics Certification Requirements and Procedures:

Error Budgets for VOR/DME RNAV, Loran-C, Omega and GPS Including Flight Technical Error

R. J. Adams

December 1981

Final Report

This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/RD-81/107	A114271	

4. Title and Subtitle	5. Report Date
AVIONICS CERTIFICATION REQUIREMENTS AND PROCEDURES: Error Budgets for VOR/DME-RNAV, Loran-C, Omega and GPS Including Flight Technical Error	December 1981
	6. Performing Organization Code
7. Author(s) R.J. Adams	8. Performing Organization Report No.
9. Performing Organization Name and Address Systems Control Technology, Inc. 2326 So. Congress Ave West Palm Beach, FL 33406	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. DTFA-01-80-4-10581
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, DC 20591	13. Type of Report and Period Covered Interim Report Task 003
	14. Sponsoring Agency Code ARD-310

15. Supplementary Notes

Formerly Systems Control, Inc. (Vt)

16. Abstract

This study was performed to assess the availability and applicability of available error budget data for avionics certification requirements. The investigation includes a review of data for both station oriented (VOR/DME-RNAV) navigation systems and wide area (Loran-C, Omega and GPS) navigation systems. The primary thrust of the analysis was to determine the operational capabilities of the various navigation systems currently being certified. A secondary objective was to examine the viability of current certification procedures, techniques and accuracy criteria to any advanced navigation system. To accomplish these objectives, a detailed assessment of error budget data, error combination techniques and functional performance standards was performed.

17. Key Words	18. Distribution Statement
Avionics Standards Accuracy Requirements Flight Technical Error Error Budgets RNAV	Availability unlimited. Document may be released to the National Technical Information Service, Springfield, VA 22161, for sale to the public

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	159	

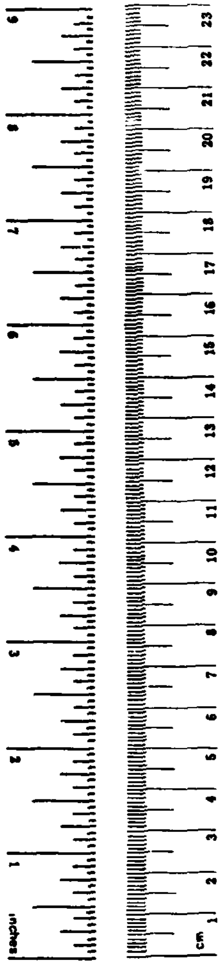
Form DOT F 1700.7 (8-72)

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

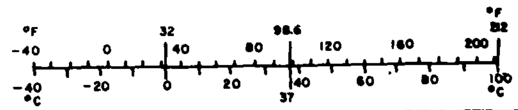


TABLE OF CONTENTS

TABLE OF CONTENTS - Continued

LIST OF TABLES

LIST OF TABLES - Continued

LIST OF FIGURES

AVIONICS CERTIFICATION REQUIREMENTS AND PROCEDURES:

Error Budgets for VOR/DME RNAV, Loran-C, Omega and GPS Including Flight Technical Error

1.0 INTRODUCTION AND BACKGROUND

The analysis presented in this document summarizes the results of a preliminary error budget data base investigation. This investigation included a review of the available data for both station oriented (VOR/DME-RNAV) navigation systems and wide area (Loran-C, Omega and GPS) navigation systems. This study was performed for the Systems Research and Development Service of the Federal Aviation Administration (FAA) under subcontract from T.S. Infosystems, Inc. The primary thrust of this effort was to determine the operational capabilities of the various navigation system alternatives from an accuracy viewpoint. To accomplish this goal it was necessary to evaluate both the station oriented and the wide area coverage systems using a consistent definition of the air traffic control (ATC) environment, to determine relative performance capabilities through an error budget analysis and to examine the impact of the present error combination techniques on the determination of system accuracy.

1.1 CENTRAL ISSUE

The basic need for the current effort is derived from the contrast that exists between the proliferation of a multitude of microprocessor based area navigation systems and the very limited FAA experience to date with certification of these advanced digital navigation systems. Currently, the FAA is faced with developing certification criteria while simultaneously evaluating digital avionics systems for the DC9-80, the U.S. Coast Guard SRR helicopter, the Falcon-50, the Boeing B-757, B-767, the Airbus A-310, etc. In addition to these highly visible programs, there is currently a large demand from the general aviation community for advanced navigation systems (over 27,000 units sold as of July 1981). These systems must perform satisfactorily from the viewpoints of the air traffic controller, the pilot and the certifying authority. For this reason, this error budget analysis cannot be performed in a closed environment. The error budget and system accuracy issues must be considered vital in determining airspace limitations, flight procedures

and avionics standards. Consequently, this error budget analysis addresses system performance from each of these three viewpoints. In particular, system performance is addressed with the following perspectives in mind:

1. Airspace Issues
    a. What are the potential problems introduced by different systems operating in the same airspace?
    b. How do the signal propagation characteristics of each of the systems impact airspace required or utilized? If nominal characteristics are acceptable, what about the anomalous, error producing characteristics?
    c. How do the dynamic response characteristics of each system enhance or corrupt the steady state error budget values and overall system performance acceptance?

2. Procedures Questions
    a. How consistently do each of the systems respond to controller instructions?
    b. Are each of the systems compatible with both current and future National Airspace System (NAS) Concepts?
        - Current VOR/DME Procedures, RNAV Procedures and Distributed Management Concepts
        - Time Control, Energy Management, Flow Control
        - Others

Answers to these avionics standards issues do not necessarily form the bulk of the analysis which follows. However, these questions do have a significant impact on how that analysis was performed. Answers to these questions are both implicit and explicit in the method of approach and problem definitions which follow.

The crux of this report will focus on the avionics standards issues for both station-oriented and wide area coverage navigation systems. These issues include functional characteristics, operational characteristics, error budgets, error combination procedures and evaluation techniques which may improve the certification process.

1.2 PROBLEM OVERVIEW

The classical approach to the certification of advanced area navigation avionics systems is exemplified by the FAA Advisory Circular 90-45A.[1] This document provides approval guidelines in the form of:

1) Acceptable Means of Compliance with Airworthiness Regulations.
2) Procedures for Obtaining FAA Data Approval by Supplemental Type Certificate (STC) or Major Repair and Alteration (Form 337).
3) Sources of Navigation System Error
4) Instrument Flight Procedures and Criteria for Enroute, Terminal and Instrument Approaches.
5) Computation of Crosstrack and Alongtrack Error Components.

This document (AC-90-45A) provides approval criteria for both VOR/DME dependent systems and "self-contained systems such as Inertial Navigation Systems (INS)". The basis for the approval criteria and procedures is heavily dependent upon the FAA's VOR/DME experience. For example, VOR and DME signal in space accuracies have been verified through the use of SAFI flight test results and the coverage limits are fixed, based on the definition of terminal, high and low VOR facilities. Neither of these criteria are applicable to wide area coverage systems such as Loran-C, Omega or GPS. There is no current effort to establish analogous signal-in-space performance or coverage limitations for these wide area systems. The equipment certification process in AC90-45A is based on known VOR/DME technologies such as standard bench test, environmental tests, installed system functional tests and flight checks for system accuracy. These procedures are all valid for a well defined avionics system based solely on VOR/DME. However, for other advanced digital systems these approval procedures do not adequately define several important system design issues. The classical approach to navigation system certification does not address the importance or impact of:

1. Automatic Station Selection
2. Poor Geometry - GDOP

3. Dynamic Signal Coverage Regions
4. Acquisition Time Effects
5. Reacquisition Time/Capability
6. Degraded Mode of Performance
7. Failure Warning Logic
8. Long Signal Filter Time
9. Charting

Of these nine issues, numbers 1, 4, 6, 7 and 9 are important to the more sophisticated VOR/DME RNAV systems as well as to the wide area coverage systems. For example, the protected airspace on either side of a SID or STAR route in the terminal area has typically been designed using the terminal VORTAC at the primary airport in the area. Yet, multi-receiver VOR/DME systems which station select may or may not be using that station as the primary input for the entire SID or STAR. Microprocessor based, multi-sensor systems which use sophisticated filtering and weighting techniques may use the terminal VORTAC as only one in a series of inputs to the navigation calculations. Table 1.1 provides a partial list of the wide variety of VOR/DME-RNAV and wide area coverage systems currently in use. The diversity of hardware and software implementations is obvious for all categories except GPS. The very foundation of the classical certification process, namely AC90-45A, is not necessarily the best means for certification of even the commonplace VOR/DME navigation system for which it was developed.

The importance of the preceding analysis and statement can be appreciated by examining the data shown in Figure 1.1. This figure shows the extremely large number of systems (over 27,000 total) already sold as of July 1981. The data in Figure 1.1 also illustrates the diversity of system types currently approved for the NAS. For example, over 5000 single waypoint, analog KN-74 systems and over 6000 digital, multiwaypoint KNS80 VOR/DME systems, along with large numbers (approximately 2000 each) of the ONS-25 Omega and the GNS-500A VLF/Omega. This figure was prepared to point out that the certification issue and especially the error budget/accuracy issue is not a trivial one. Large numbers of potentially incompatible systems have already been sold without sufficient

Table 1.1 Summary of Current VOR/DME-RNAV and Wide Area Coverage Navigation Systems

System Type	Manufacturer	Model Number	Characteristic User
1. VOR/DME RNAV	King	KN-74	Simple, G.A.
	Foster Air Data	AD-511/612	Simple, G.A.
	Cessna ARC	Cessna 800/400	Simple, G.A.
	King	KNS-80	Sophisticated, G.A.
	King	KNC-610	Sophisticated, G.A.
	Collins	ANS-31	Sophisticated, G.A.
	Bendix	NCP-2040	Sophisticated, G.A.
	J.E.T. Electronics	DAC 2000/7000	Commuter/Business
	Garrett	Airnav 300B	Commuter/Business
	Collins	ANS 70A	Air Carrier
	Sperry	Tern 100	Air Carrier
2. Loran-C	Teledyne	TDL-711	Simple, G.A.
	Teledyne	TDL-424	Air Carrier
	Austron/ONI	ONI-7000	Commuter/Business
	Texas Instruments	TI-9000/9100	Commuter/Business
3. Omega-Omega/VLF	Canadian Marconi	CMA 771/734	Business/Air Carrier
	Collins	LRN 70/80/85	Business/Air Carrier
	Tracor	Tracor 7800	Business/Air Carrier
	Global Navigation	GNS 500A	Business/Air Carrier
	Bendix	ONS 25	Business/Air Carrier
	Litton	LTN-211/3000	Business/Air Carrier
	Norden	ONS-VII	Business/Air Carrier
4. Global Positioning System	Magnavox	Z-Set	G.A., Business, Commuter

G.A. - General Aviation

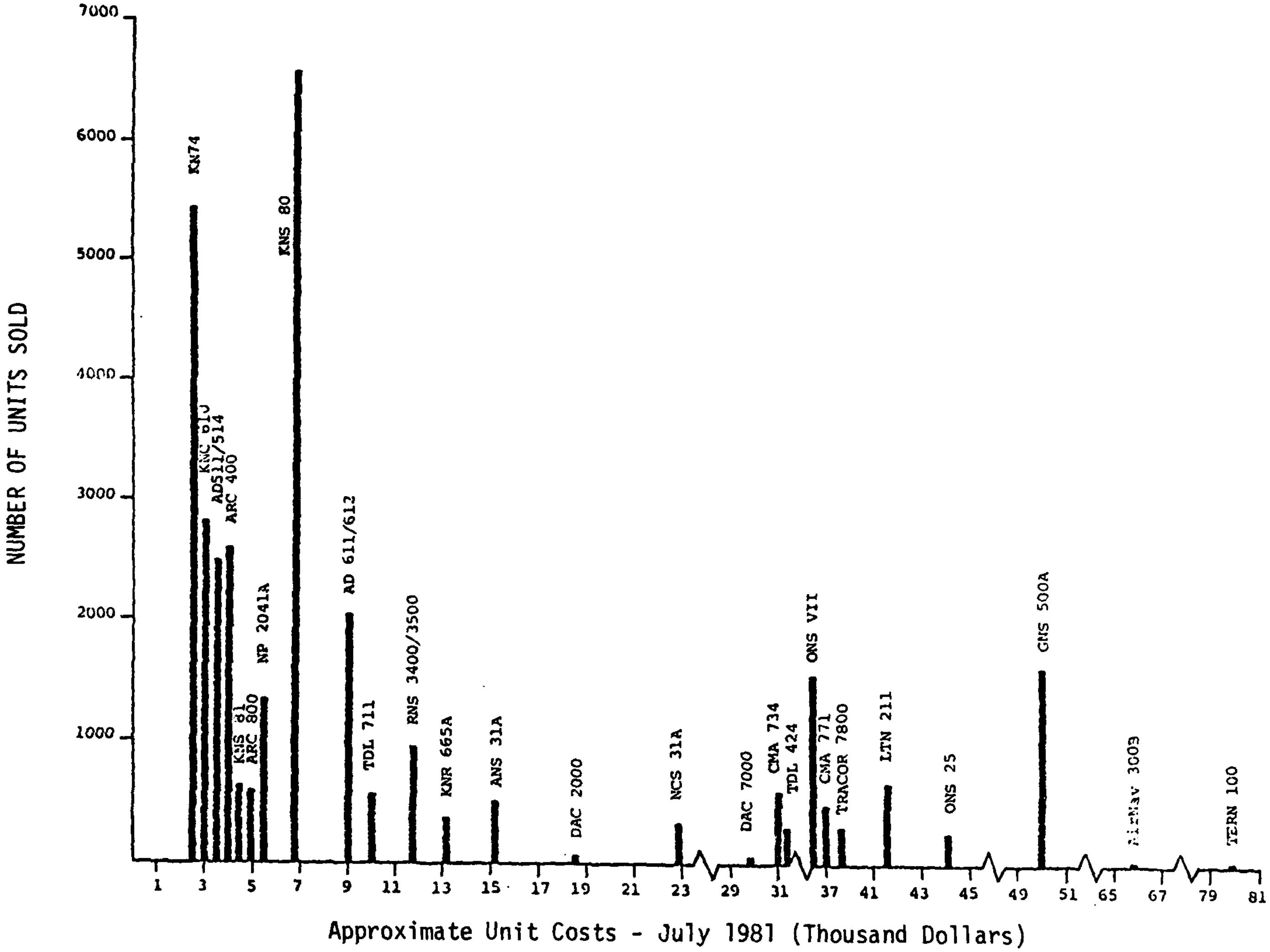


Figure 1.1 Distribution of Navigation Systems By Cost and Type

standardized evaluation of the potential impact on accuracy, airspace and procedures.

What is needed to resolve this dilemma? Navigation system error characteristics must be analyzed for VOR/DME-RNAV, Loran-C, Omega and GPS. This analysis must evaluate the compatibilities and incompatibilities of the various advanced digital systems. As a minimum the following critical issues must be addressed for each generic type of navigation system.

1. The Impact of ATC Procedures on Airspace
2. The Impact of Pilot/Autopilot Techniques on Airspace
3. The Impact of Navigation Computer Decision Making on Airspace
4. The Route Width Requirements for Each Navigation System
5. The Turn Overshoot/Undershoot Areas Required
6. The Effects of Error Budget on Route Widths
7. The Impact of Error Combination Techniques on Route Widths

In order to properly quantify these interrelationships, a twofold effort is required. First, the appropriate error budgets for each system type must be determined through either existing flight test or simulator data. Second, the method in which each system's errors combine must be determined accurately enough to replicate actual system performance based on assessment of individual error elements. In order to accomplish these goals, innovative techniques of error analysis, error correlation and sytem interactions must be performed. Additionally, in contrast to the simplified system approval procedures with which AC90-45A currently operates, it will be necessary to develop certification procedures which can be used to evaluate both static and dynamic system performance without requiring large amounts of actual flight testing.

1.3 OBJECTIVES AND PRODUCTS

In order to resolve the issues described in Section 1.2 it was necessary to develop a methodical approach to the analysis of advanced digital navigation system performance. The thrust of that approach is presented in detail in the following test. The foundation for this analysis was based on satisfying the following specific objectives:

1. To establish criteria by which systems can be certified including -
   a) Error budgets
   b) Error combination techniques
   c) System accuracy
2. To formulate certification procedures for -
   a) Bench tests
   b) Simulation tests
   c) Flight tests
3. To develop certification philosophy

   To define techniques for verifying compliance -
   a) Data Requirements
   b) Analysis Techniques
   c) Flight Demonstrations

The basic products associated with satisfying these four primary objectives will be in the form of error budgets and error combination techniques for VOR/DME-RNAV, Loran-C, Omega and GPS. Figure 1.2 was prepared to provide an understanding of how these error quantities are related to the broader issues of airspace, procedures and total system accuracy. As shown in the figure, four navigation system error characteristics must be determined for each generic system:

1.	Ground System Error	-	Signal-In-Space Error Characteristics
2.	Airborne System Error	-	Receiver Processing and Filtering Effects
3.	Navigation Computer Error	-	Navigation and Propagation Equations
4.	Pilot Error	-	Flight Technical Error

These four error budget quantities combine in the real system (comprised of aircraft, avionics and pilot) to form the quantity referred to as "Total System Error". It is the Total System Error magnitude which determines certifiability from an accuracy viewpoint.

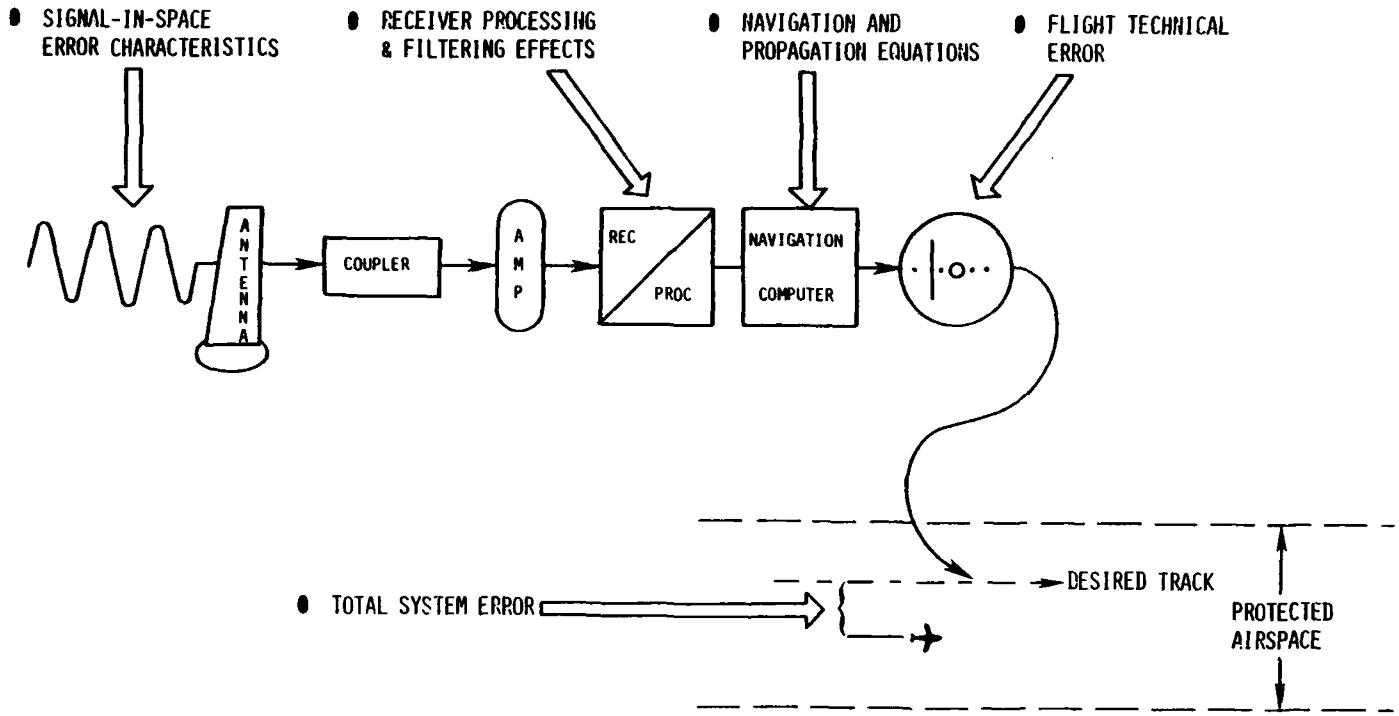


Figure 1.2 Navigation System Error Budget Characteristics Related to Total System Error and Airspace Requirements

This parameter also relates directly to airspace requirements as shown in Figure 1.1. The purpose of the current effort is to quantify the four basic error parameters for each navigation system of interest and to develop an error combination technique which combines these four parameters into a reliable and accurate estimate of Total System Error.

2.0 OPERATIONAL AVIONICS REQUIREMENTS

As stated in the introductory section, advanced navigation system performance goals and error budget capabilities are impacted by considerations outside of the cockpit. Analysis of these considerations provides insight into both minimum equipment characteristics and pilot-related workload and accuracy requirements. Assume, for the moment, that a pure RNAV environment is operational and the usage of radar vectors by ATC has been eliminated. The most noticeable observation which immediately stands out is the existing proliferation of area navigation (RNAV) systems of widely varying capabilities. Systems ranging from the very low cost, single waypoint analog types to the very sophisticated airline quality systems are co-mingled in the operational environment referred to as the National Airspace System (NAS). Since it is the function of the air traffic controller to maintain order from this wide variety of aircraft, RNAV and pilot capabilities, certain ground rules must be established. In the most basic form these rules can be stated as follows:

1) Segregation of aircraft by RNAV system type is <u>not</u> reasonable from an ATC viewpoint.
2) Compatibility of aircraft paths must be achieved for all the various equipment levels in response to a specific area navigation instructions by ATC.
3) Repeatability of aircraft paths must be insured for each of the RNAV procedures utilized by ATC regardless of pilot experience.

Although these rules or assumptions were postulated for a pure RNAV environment void of radar vectors, the validity of these assumptions is retained even in a mixed RNAV/radar vector environment. It could be argued that the validity is enhanced in the mixed environment. These three basic ground rules are utilized for the operational requirements which affect the error budget analysis.

2.1 SYSTEM DESIGN REQUIREMENTS

The importance of operational assumptions of system design requirements has been recognized and formalized in the Federal Radionavigation Plan (FRP) Volume II.[2] Chapter 2 of the FRP entitled "Civil Air Radionavigation Requirements" presents a more detailed, 24 item set of operational constraints. As stated in the FRP:

> "Aircraft separation criteria, established by the Federal Aviation Administration (FAA) take into account limitations of the navigational service available, and in some airspace the Air Traffic Control (ATC) surveillance service. Aircraft separation criteria are influenced by the quality of navigational service, but are strongly affected by other factors as well. The criteria relative to separation require a high degree of confidence that an aircraft will remain within its assigned volume of airspace. The dimensions of the volume are determined by a stipulated probability that performance of the navigational system will not exceed a specified error".

In order to insure that proper separation is achieveable on a repeatable basis, the advanced navigation systems must be designed to, and perform within, the same operational aviation environment. This requires careful consideration of several basic design elements. To provide the FAA's assessment of what the navigation system design constraints are, the FRP requirements have been extracted as follows:

A. *The system must be suitable for use in all aircraft types which may require the service without unduly limiting the performance characteristics of those aircraft types, e.g., maneuverability and fuel economy.*

B. *The system must be safe, reliable, available and capable of providing service over all the used airspace of the world, regardless of time, weather, terrain and propagation anomalies.*

C. *The overall integrity of the system, including the presentation of information in the cockpit, shall be as near 100 percent as is achievable and to the extent feasible should provide flight deck warnings in the event of failure, malfunction, or interruption.*

D. *The system must have a capability of recovering from a temporary loss of signal in such a manner that the correct current position will be indicated without the need for complete resetting.*

E. *The system must automatically present to the pilot adequate warning in case of malfunctioning of either the airborne or source portions of the system, and assure ready identification of erroneous information which may result from a malfunctioning of the whole system or incorrect setting.*

F. *The system must provide in itself maximum practicable protection against the possibility of input blunder or misinterpretation of output data.*

G. *The system must provide adequate means for the pilot to check the accuracy of airborne equipment.*

H. *The system must employ navigational information source equipment which automatically and radically changes the character of its indication in case a divergence from accuracy occurs outside safe tolerance.*

I. *The system must employ navigational information source equipment which provides immediate and positive indication of malfunction.*

J. *The navigational information provided by the system must be free from unresolved ambiguities of operational significance.*

K. *Any source-referenced component of the total navigation system shall be capable of providing navigational information simultaneously and instantaneously to all aircraft which require it within the area of coverage.*

L. *The navigation system must be capable, in conjunction with other flight instruments, of providing to the pilot in convenient, natural, and rapidly assimilable form in all circumstances, and the appropriate phases of flight, information directly applicable to the handling of the aircraft, for the purpose of:*

1. *Continuous track guidance.*
2. *Continuous determination of distance along track.*
3. *Continuous determination of position of aircraft, as resolved by the navigation system.*
4. *Position reporting.*
5. *Manual or automatic flight.*

The system shall also provide for input and utilization of the above in conveniently operable form; and must permit design of indicators and controls which can be directly interpreted or operated by the pilot at his normal station aboard the aircraft.

M. *The system must be capable of being integrated into the overall ATC, communications, and navigation system.*

N. *The system should be capable of integration with all phases of flight, including the precision approach and landing system.*

O. *The system must permit the pilot to determine the position of the aircraft with an accuracy and frequency such as to ensure that the separation minima used can be maintained at all times, execute accurately the required holding and approach patterns, and to maintain the aircraft within the area allotted to the procedures.*

P. *The system must permit the establishment and the servicing of any practical, defined, route structure for the appropriate phases of flight as required.*

Q. *The system must have sufficient flexibility to permit changes to be made to the air-route structure and siting of holding patterns without imposing unreasonable inconvenience or cost to the providers and the users of the system.*

R. *The system must be capable of providing the information necessary to permit maximum utilization of airports and airspace.*

S. *The system must be cost-effective to both government and users.*

T. *The system must employ equipment such as to minimize susceptibility to interference from adjacent radio-electronic equipment and shall not cause objectionable interference to any associated or adjacent radio-electronic equipment installation in aircraft or on the ground.*

U. *The system must be free from signal or signal-to-signal plus noise ratios below which the system cannot operate in the operating area.*

V. *The system avionics must be comprised of the minimum number of elements which are simple enough to meet, economically and practically, the most elementary requirements, yet be capable of meeting, by the addition of suitable elements, the most complex requirements.*

W. *The system must be capable of furnishing reduced service to aircraft with limited or partially inoperative equipment.*

X. *The system must be capable of integration with the flight control system of the aircraft to provide automatic tracking.*

Of these 24 operational system design requirements, items D, E, G, H, J, L, O, P, U and X are particularly pertinent to a system accuracy and error budget assessment. These requirements explicitly define the necessary signal-in-space or ground system operating constraints, the impact on pilot workload and the airspace/phase-of-flight constraints within which all navigation equipment must function. These operational requirements were developed by the FAA to insure non-derogation of service to all users of the airspace and to promote aviation safety. As such, these air navigation system requirements explicitly recognize

that navigation is only one of a multitude of tasks performed by the pilot. Therefore, the workload for navigation, in conjunction with communications, flight control and engine monitoring, must be low enough so that the pilot has adequate time to perform safely in the NAS and to avoid other aircraft operating under the basic FAA "see-and-avoid" rules. Unfortunately, adequate procedures for demonstrating navigation system compliance with the operational requirements of the FRP do not currently exist.

2.2 SYSTEM INTEGRATION REQUIREMENTS

In addition to the fundamental system design constraints of the previous section, there are other serious avionics system integration requirements which are derived from the mixed operating environment. These integration requirements stem from the mixed navigation environment in which conventional radial flight (VOR/DME), VOR/DME direct routing (RNAV) and non-VOR/DME or wide area coverage RNAV systems must coexist. In order to safely and efficiently operate in the integrated NAS environment, advanced digital navigation systems must be designed such that "all airborne operations responding to like controller instructions will result in similar maneuvering of the aircraft, regardless of system type".[3] This principle is the basic tenet of Special Committee (SC)137 of the Radio Technical Commission for Aeronautics (RTCA). This committee was formed in 1978 to develop Minimum Operational Performance Standards (MOPS) for both VOR/DME and wide area coverage RNAV systems. This group is comprised of regulatory personnel (FAA), manufacturers, operators and researchers. The group's ideas represent a knowledgeable consensus of current navigation system capabilities and constraints. The document being prepared by this group, when completed, will be submitted to the FAA for consideration in the development of a TSO for certification of all future navigation systems. Due to the importance of this effort, and being pertinent to the current discussion and the potential impact on system certification, it is appropriate to review the operational environment envisioned by this group and evaluate the impact of their viewpoint on air traffic separation requirements, navigation system accuracy and error budgets.

An integral part of the SC-137 effort has been to evaluate, in detail, the existing requirements for route widths and lateral separation in the enroute and terminal environments. From this evaluation of current aircraft separation standards (navigation system accuracy requirements) and a working knowledge of both the ATC system and the advanced digital avionics systems (manufacturers and operators), an operational environment was defined. The purpose of this environment as stated by the committee was to understand:

- Airborne systems' functional and accuracy requirements
- Applications of area navigation in the ATC system
- Present limitations of the ATC system and area navigation system which must be recognized and accommodated either through ATC procedures, airborne system improvements, pilot procedures, or other means.

The detailed description of this environment may be found in the Fifth Draft of the MOPS dated August 7, 1981 (RTCA Paper No. 251-81/SC137-52).[4] This description will be summarized here and the areas directly applicable to system accuracy, error budget analysis and system certification will be highlighted. The need for this review is twofold. First, it is necessary to understand the different operating conditions which impact accuracy requirements. Second, it is needed to explicitly illustrate that comparison of systems based solely on a set of error budget numbers or based upon a single number for total system accuracy can be very misleading.

Fundamental to the postulated SC-137 operational environment is a basic assumption that, given an airborne capability that will adequately comply with ATC RNAV maneuver instructions, the ATC system will use RNAV capabilities in the control of traffic when such use will not degredate the safe and expeditious flow of traffic. This basic assumption in conjunction with the assumptions listed in Table 2.1, allow for the evaluation of RNAV in a mixed environment in which the RNAV user represents a minority group of the total ATC system users as well as in an environment wherein the RNAV-equipped traffic may represent a majority. It is anticipated that as the number of

Table 2.1 Summary of the Postulated Area Navigation Operational Environment[4]

1. ATC SYSTEM ACCOMMODATES BOTH RNAV AND RADIAL NAVIGATION FLIGHT OPERATIONS.

   FLIGHTS EQUIPPED WITH AREA NAVIGATION SYSTEMS ARE CLEARED VIA:

   A. CHARTED HIGH ALTITUDE 2D RNAV ROUTES,
   B. CHARTED LOW ALTITUDE 2D RNAV ROUTES,
   C. DIRECT POINT-TO-POINT BETWEEN ESTABLISHED WAYPOINTS AND/OR IMPROMPTU WAYPOINTS,
   D. CHARTED HIGH ALTITUDE JET ROUTES AND LOW ALTITUDE AIRWAYS,
   E. DIRECT POINT-TO-POINT BETWEEN VORS AND/OR VORTACS,
   F. ESTABLISHED SIDS AND STARS DEFINED IN PART OR IN WHOLE BY VOR RADIALS,
   G. ESTABLISHED SIDS AND STARS DEFINED IN PART OR IN WHOLE BY WAYPOINTS,

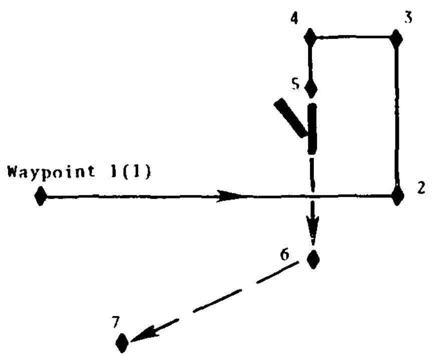


Figure 1

   H. RADAR VECTORS AS APPROPRIATE FOR NAVIGATION AND SEPARATION,
   I. ASSIGNED HEADING UNTIL REACHING A GIVEN ALTITUDE OR DISTANCE BEFORE PROCEEDING DIRECT TO A SPECIFIED WAYPOINT (see Figures 2 and 3).

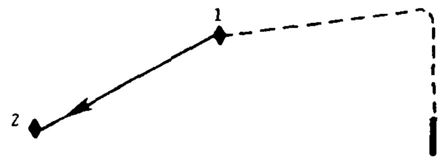


Figure 2

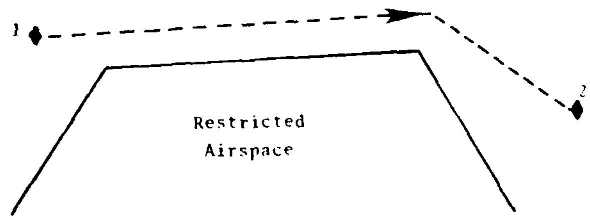


Figure 3

2. AREA NAVIGATION APPROACHES ARE DEFINED AND APPROVED FOR USE. APPROACHES MAY BE BASED ON 2D AND/OR 3D AREA NAVIGATION CAPABILITIES.

3. AREA NAVIGATION MANEUVERS ARE USED BY ATC TO ACCOMPLISH DEVIATIONS FROM ESTABLISHED OR PREVIOUSLY CLEARED ROUTES OR DIRECT FLIGHT PATHS IN THE CONTROL OF AREA NAVIGATION FLIGHTS.

Table 2.1 Summary of the Postulated Area Navigation Operational Environment[4] (continued)

THESE MANEUVERS INCLUDE:

A. PARALLEL OFFSETS, IN 1-MILE INCREMENTS, RIGHT/LEFT OF PARENT ROUTE SEGMENT OR SERIES OF SEGMENTS FORMING EITHER A STRAIGHT LINE OR ANGLE(S). IT IS ANTICIPATED THAT THE MAXIMUM PARALLEL OFFSET DISTANCE REQUIRED BY THE ATC SYSTEM WILL BE 20 NMI (see Figure 4).

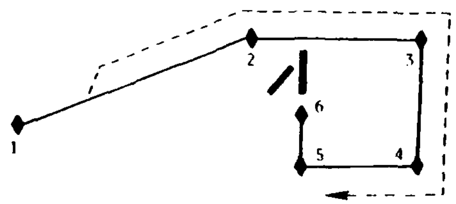


Figure 4

B. CANCELLATION OF A PREVIOUSLY ISSUED OFFSET BY CANCELLATION OR DIRECT TO INSTRUCTION (see Figures 5 and 6)

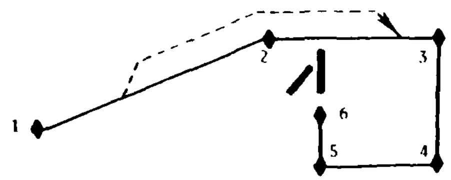


Figure 5

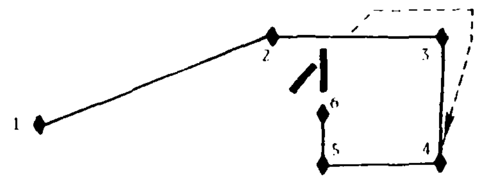


Figure 6

C. INCREASING OR DECREASING THE PARALLEL OFFSET DISTANCE PREVIOUSLY ISSUED (see Figure 7).

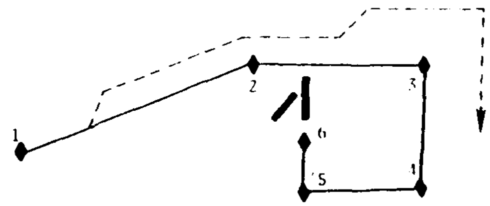


Figure 7

D. MAINTAINING PRESENT TRACK WHILE NAVIGATING ALONG A PARALLEL OFFSET SEGMENT UNTIL INTERCEPTING THE NEXT ROUTE SEGMENT FORMING AN ANGLE TO THE PRESENT TRACK (see Figure 8).

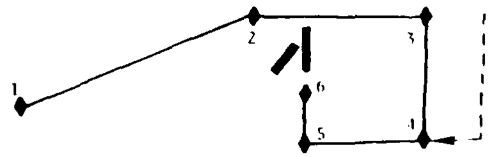


Figure 8

Table 2.1 Summary of the Postulated Area Navigation Operational Environment[4] (continued)

E. MAINTAINING PRESENT TRACK WHILE NAVIGATING ALONG A PARENT ROUTE SEGMENT UNTIL INTERCEPTING A SPECIFIED PARALLEL OFFSET TO THE NEXT ROUTE SEGMENT FORMING AN ANGLE TO THE PRESENT TRACK (see Figure 9).

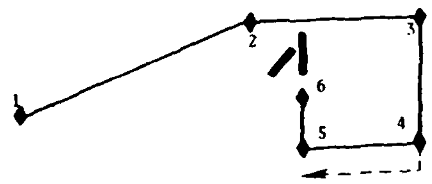


Figure 9

F. RADAR VECTORS TO INTERCEPT A PARENT ROUTE SEGMENT OR SPECIFIED PARALLEL OFFSET (see Figure 10).

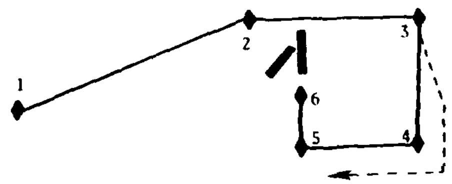


Figure 10

G. DIRECT NAVIGATION TO EITHER A CHARTED OR UNCHARTED WAYPOINT (see Figures 11 and 12).

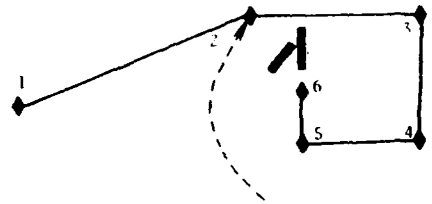


Figure 11

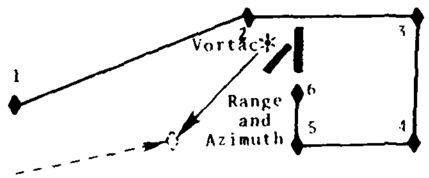


Figure 12

H. CLIMB OR DESCEND SO AS TO CROSS A SPECIFIED WAYPOINT OR OFFSET POSITION OF WAYPOINT AT OR ABOVE, OR AT OR BELOW A SPECIFIED ALTITUDE.

I. MAINTAINING A SPECIFIED ALTITUDE UNTIL PASSING A GIVEN WAYPOINT.

J. CLIMB/DESCEND SO AS TO REACH A SPECIFIED ALTITUDE (OR MAINTAIN A SPECIFIED ALTITUDE UNTIL) A GIVEN DISTANCE PRIOR TO OR AFTER PASSING A SPECIFIED WAYPOINT.

K. HOLDING AT A SPECIFIED WAYPOINT

4. VNAV IS USED AS A PILOT AID FOR ENROUTE AND SID/STAR NAVIGATION IN THAT *CONTROL CLEARANCES AND ROUTE* STRUCTURE DESIGNS ARE NOT PREDICATED ON ITS USE. WHEN APPLICABLE, PILOTS WILL USE VNAV GUIDANCE AS IDENTIFIED IN ASSUMPTION 2 AND FOR ECONOMIC, COMFORT OR OTHER REASONS WHEN SUCH USE DOES NOT VIOLATE ATC CLEARANCES.

Table 2.1 Summary of the Postulated Area Navigation Operational Environment[4] (continued)

5. CARRIAGE OF AREA NAVIGATION AVIONICS SYSTEMS IS NOT REQUIRED BY THE FAA.

6. ALL AREA NAVIGATION CHARTED ROUTES ARE DEFINED BY WAYPOINTS BASED ON RANGE AND AZIMUTH FROM VORTAC STATIONS AND LAT. AND LONG. NONCHARTED WAYPOINTS (NOT PUBLISHED) DESIGNATED BY AN AIR TRAFFIC CONTROLLER WILL BE DEFINED REFERENCE VORTAC FACILITIES ONLY.

7. AREA NAVIGATION WILL CONTINUE TO BE USED FOR THE CONDUCT OF BOTH IFR AND VFR OPERATIONS.

8. HELICOPTER AS WELL AS FIXED-WING AIRCRAFT WILL USE RNAV SYSTEMS.

9. CURRENT ROUTE WIDTHS WILL BE USED.

10. 4D RNAV MAY BE USED TO ACHIEVE ASSIGNED ARRIVAL/DEPARTURE TIMES AT ARRIVAL FIXES BY SPEED ADJUSTMENT DETERMINED BY THE AIRBORNE SYSTEM IN AN ENROUTE METERING TERMINAL PROFILE DESCENT ENVIRONMENT.

11. BASED ON THE USE OF AREA NAVIGATION MANEUVERS TO ACCOMPLISH METERING AND SPACING, THE FOLLOWING MANEUVERS WOULD BE FLOWN BY 2D RNAV SYSTEM USERS:

A. "FAN" MANEUVERS WILL BE FLOWN FOR PATH STRETCHING--THE FAN WOULD CONSIST OF A TURN RIGHT OR LEFT OF COURSE AT 45°* TO SOME SPECIFIED PARALLEL OFFSET DISTANCE. PRIOR TO REACHING THAT DISTANCE, THE FLIGHT WOULD BE CLEARED DIRECT TO THE NEXT OR A SUBSEQUENT WAYPOINT ALONG THE STAR (see Figures 13 and 14).

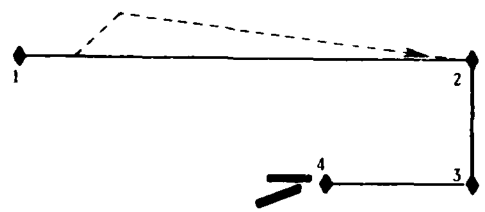


Figure 13

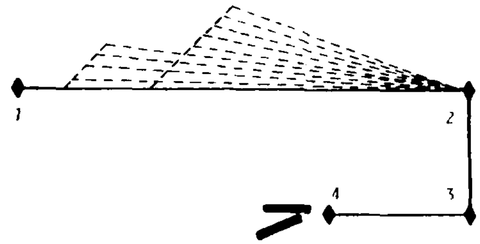


Figure 14

B. EXTENDED DOWNWIND LEG

(1) BY MAINTAINING DOWNWIND SEGMENT TRACK TO INTERCEPT A GIVEN BASE LEG SEGMENT PARALLEL OFFSET (see Figure 9).

(2) BY PROVISION OF ONE OR MORE CHARTED WAYPOINTS FOR IMPROMPTU ASSIGNMENT (see Figures 15 and 16).

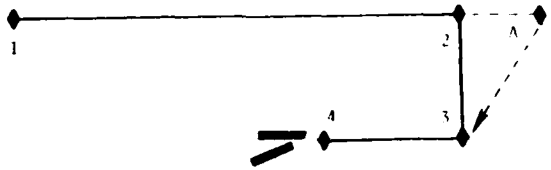


Figure 15

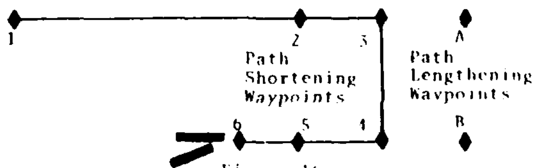


Figure 16

Table 2.1 Summary of the Postulated Area Navigation Operational Environment[4] (continued)

(3) BY USE OF A FAN MANEUVER ON BASE LEG (see Figure 17)

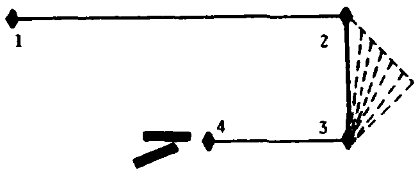


Figure 17

(4) BY DESIGNING THE RNAV STAR SUCH THAT THE DOWNWIND LEG LENGTH ACCOMMODATES MAXIMUM LENGTH REQUIREMENTS.

C. SHORTENED DOWNWIND LEG

(1) BY MAINTAINING THE DOWNWIND LEG SEGMENT TRACK UNTIL INTERCEPTING A GIVEN BASE LEG PARALLEL OFFSET (see Figure 9).

(2) BY DESIGNING THE RNAV STAR SUCH THAT THE MINIMUM LENGTH DOWNWIND LEG SEGMENT IS THE CHARTERED ROUTE.

(3) BY CHARTING ADDITIONAL WAYPOINTS ALONG THE DOWNWIND AND FINAL APPROACH SEGMENT FOR IMPROMPTU ASSIGNMENT FOR ROUTE MODIFICATION (see Figure 16).

D. BASE LEG ROUTE SEGMENTS WOULD BE LENGTHENED THROUGH USE OF A "FAN" (see Figure 17).

E. BASE LEG ROUTE SEGMENTS WOULD BE SHORTENED BY:

(1) CLEARANCE DIRECT TO A WAYPOINT ON THE FINAL APPROACH COURSE.

(2) RADAR VECTORS TO INTERCEPT THE FINAL APPROACH COURSE.

13. IF 4D AREA NAVIGATION HAS BEEN INCORPORATED IN THE TERMINAL AREA METERING AND SPACING SYSTEM, THE GROUND-BASED SYSTEM MAY GENERATE PATH-STRETCHING/SHORTENING MANEUVER INSTRUCTIONS AND TIMES TO BE MADE GOOD AT ONE OR MORE WAYPOINTS ALONG THE STAR. THE AIRBORNE SYSTEM CAN PROVIDE SPEED ADJUSTMENT INFORMATION TO THE PILOT-- THIS MAY REQUIRE THAT THE AIRBORNE SYSTEM CALCULATE SPEED TO ACHIEVE A TIME AT THE APPROACH GATE, OR CALCULATE BOTH SPEED AND TIME TO BE MADE GOOD AT INTERMEDIATE POINTS ALONG THE ROUTE.

RNAV-equipped operations increases, controller familiarity with the use of RNAV in the ATC system will also increase. This, in turn, will increase the use of RNAV maneuver capabilities and assignment of RNAV routes (both charted and uncharted).

2.3 OPERATIONAL REQUIREMENTS AND NAVIGATION SYSTEM ERROR CHARACTERISTICS

The detailed set of advanced navigation system operational requirements which have been developed from:

a. The three basic assumptions
b. The Federal Radionavigation Plan
c. The SC-137 MOPS Committee

comprise the best known set of operating conditions. These constraints satisfy the basic requirements for aviation safety and the promotion of aviation growth. However, these conditions impact different navigation systems to differing degrees. It is necessary, therefore, to examine the interaction between these operational requirements and the basic navigation system error characteristics that need to be analyzed.

The unique signal characteristics of VOR/DME-RNAV, Loran-C, Omega and GPS have a direct effect on determining achieveable minimum route widths. The distribution and rate of change, as well as magnitude of the error characteristics of each system must be considered. Error distributions may contain both bias and random components. The bias component is generally easily compensated for when its characteristics are constant and known. For example, VOR radials can be flight-checked and the bias error reduced or eliminated through correction of the radial used on aeronautical charts. Similarly, slowly varying errors such as the seasonal and diurnal variations of Loran-C can also be compensated for in some systems by implementing correction algorithms in aircraft equipment logic.

In contrast, the distribution of the random varying error component becomes the critical element to be considered in the evaluation and certification of navigation systems. For any selected route width and system accuracy, those systems which have a

broad error distribution tend to produce a higher risk of collision than those with a narrow distribution. The rate of change of the error within the distribution is also an important factor, especially when the system is used for approach. Errors varying at a very high frequency can be readily filtered out in the airborne equipment. Errors occurring at a slower rate can, however, be troublesome and result in disconcerting indications to the pilot. An example of one of those would be an apparently moving runway as the aircraft equipment responds to the slowly varying error and the pilot follows the course deviation indicator (CDI) needle to maintain what is believed to be the proper non-precision approach course. This indication can be further aggravated if navigation systems exhibit different error characteristics during different phases of flight or when the aircraft is maneuvering.

The method of determining the total system error is affected by the navigation signal error characteristics, the error budget elements and the error combination technique. In most current systems the error components are ground system errors, airborne receiver errors, navigation computer errors, and flight technical errors. These errors are combined using the root-sum-square (RSS) method. In analyzing new systems it may be necessary to use other methods of combining errors, but each element must be properly considered.

In summary, the magnitude, nature, and distribution of errors as a function of time, terrain, aircraft type, aircraft maneuvers, and other factors must be considered. The evaluation of errors is a complex process and the comparison of systems based upon a single error number will be misleading. Section 3.0 will discuss the existing error budget data for the various classes of advanced navigation systems as well as a recommended means of error combination. However, before getting into these specifics, it is necessary to investigate system evaluation procedures that could be used to quantify the dynamic system performance.

2.4 AN ADVANCED NAVIGATION SYSTEM EVALUATION/CERTIFICATION APPROACH

Recognizing the complexity of the evaluation problem for advanced digital navigation systems and the need for a certification process, RTCA SC-137 has developed detailed recommendations for these

procedures. The test procedures and associated limits specified in the Fifth Draft MOPS[4] are designed to be used as a means of meeting the minimum requirements. Four types of test procedures are included which should be used at different stages of the evaluation/certification process. The procedures are:

1. Bench Tests - Results to be used as design guidance for monitoring manufacturing compliance and, in certain cases, for obtaining formal approval of equipment design and manufacture.
2. Environmental Tests - Results to be used to determine the electrical and mechanical performance of the equipment under conditions expected to be encountered in actual aeronautical operations.
3. Installed Tests - These tests are for the airborne equipment only and require the satisfactory completion of the Bench and Environmental Tests prior to the installed testing. These tests are performed both on the ground and in-flight to demonstrate functional performance in the actual operating environment.
4. Operational Tests - These tests are for the airborne equipment only and are performed in the operating environment. These tests are used to demonstrate that the system can be operated safely and can satisfy specific minimum acceptable performance functions.

These four basic types of equipment tests have been used in the past for certification of airborne avionics. In fact, both RTCA and ARINC documents have specified this level of testing for VOR receivers,

DME receivers, navigation computers, autopilots, etc. Of these four levels or types of testing, the first category - Bench Tests - provides the foundation for acceptance. In addition, Bench Tests are the cheapest to perform, provided a controlled environment and test conditions are available. Therefore, it is from bench testing that the bulk of certification data can be expected to develop. Keeping this in mind and recognizing that neither the manufacturers or the certifying agency wanted to be burdened with excessive data collection or analysis, SC-137 set out to answer the question "What is the most meaningful, straightforward way to ascertain that navigation system performance satisfies the operational constraints for aircraft separation, route widths and ATC procedures? The answer to this question was formulated using two distinct types of Bench Tests:

1. Static Tests - These tests use precise inputs to verify that input signal and data processing is accomplished such that outputs are within specified range, resolution and scale factor limits.
2. Dynamic Tests - These tests provide <u>quantitative data</u> regarding equipment performance using a <u>simplified simulation</u> of of flight conditions.

The committee specified that the equipment must be tested in all modes of operation for both functional and accuracy performance. For advanced multi-sensor systems, scanning systems or sophisticated filtering techniques, the systems must be tested for a representative number of different combinations of sensor inputs.

The specific test procedures are presented in detail in Section 2.5 of the draft MOPS.[4] These will not be presented here. However, an overview will be necessary since these procedures will be used in the following section to assess the error budget data obtained to date.

The test procedures described in the MOPS include specific test scenarios for VOR/DME based systems and general test "principles" for equipment not using VOR/DME signals. This is due in part to the fact that the committee's work on the non-VOR/DME or wide area coverage systems has not yet been completed. The MOPS also clearly states that "Although specific test procedures are cited, it is recognized that other methods may be preferred by the testing activity". In the case where other methods are used, however, it is up to the manufacturer to show that they provide equivalent information.

With these ground rules in mind, a brief review of the MOPS dynamic testing procedures will provide the basic information necessary to understand the intent of these procedures and the application of them which follows.

For VOR/DME based navigation equipment utilizing a single reference facility as the primary information input, the manufacturer must define those inputs in terms of signal parameters and accuracy criteria. Using these inputs it must be shown that the navigation system will satisfy the accuracy requirements and the functional requirements specified in the MOPS. The dynamic tests to be performed using a "simplified simulation include":

1. Dynamic Response
2. To-From Display Response
3. Waypoint or Leg Sequencing
4. Direct-To Function

The detailed test procedures and data requirements for each of these can befound in Sections 2.5.3.1 through 2.5.3.5 of the draft MOPS.[4] These will not be repeated here. However, Tables 2.2 and 2.3 are taken from the MOPS. These tables provide the detailed Dynamic Test Conditions developed jointly by the manufacturers, the operators and the regulators. The conditions listed in Tables 2.2 and 2.3 will be used to evaluate the VOR/DME-RNAV, Loran-C, Omega and GPS error budget information presented in the next section. If these Dynamic Test Conditions are accepted by the FAA based on the RTCA's recommendations, then some type of standardized dynamic simulation will have to be developed for use by the manufacturers in the certification process.

Table 2.2 Dynamic Response Test Conditions*

Test Number	Figure	Ground Speed	Point A VOR BRG/DME Dist.	Waypoint BRG/Dist.	Point B VOR BRG/DME Dist.	Tangent Dist.	Mode
I	3.2	180 kts	135°/141.4 nm	90°/100 nm	45°/141.4 nm	100 nm	Enroute
II	3.2	**	135°/141.4 nm	90°/100 nm	45°/141.4 nm	100 nm	Enroute
III	3.3	180 kts	166°/103.1 nm	90°/25 nm	14°/103.1 nm	25 nm	Enroute/Approach
IV	3.3	90 kts	166°/103.1 nm	90°/25 nm	14°/103.1 nm	25 nm	Enroute
V	3.3	**	166°/103.1 nm	90°/25 nm	14°/103.1 nm	25 nm	Enroute
VI	3.4	90 kts	174.3°/50.3 nm	90°/5 nm	5.7°/50.3 nm	5 nm	Enroute
VII	3.4	180 kts	174.3°/50.3 nm	90°/5 nm	5.7°/50.3 nm	5 nm	Enroute
VIII	3.4	**	174.3°/50.3 nm	90°/5 nm	5.7°/50.3 nm	5 nm	Enroute
IX	3.5	90 kts	135°/35.4 nm	90°/25 nm	45°/35.4 nm	25 nm	Approach
X	3.5	180 kts	135°/35.4 nm	90°/25 nm	45°/35.4 nm	25 nm	Approach

*This table was compiled from Tables 2.5 and 2.6 of Reference 4.

**Maximum ground speed allowed by design. For the current analysis 540 kts was used.

Table 2.3 Multiple Leg Dynamic Test Conditions*

Test Number	Ground Speed	Test Reference Points - VOR Deg/DME Dist.						Mode
		A	B	C	D	E	F	
		Deg. nm	Deg. nm	Deg nm	Deg. nm	Deg. nm	Deg. nm	
I	180 kts	135.0/28.3	116.6/22.4	90.0/30.0	76.0/41.3	63.4/22.4	45.0/14.1	Approach
II	**	135.0/28.3	116.6/22.4	90.0/30.0	76.0/41.3	63.4/22.4	45.0/14.1	Enroute
III	180 kts	—	116.6/22.4	90.0/30.0†	76.0/41.3	63.4/22.4	45.0/14.1†	Enroute

*This table was compiled from Table 2.7 of Reference 4.

**Maximum ground speed allowed by design. For the current analysis 360 kts was used.

†Direct-to Reference Point F from C.

3.0 ERROR BUDGET DATA AND ANALYSIS

Error budgets and operational system accuracy issues for VOR/DME-RNAV, Loran-C, Omega and GPS have been evaluated by various research organizations, to various levels of depth and with varying success for the past 25 years. As is generally the case, each research project or operational test had specific questions to answer which led to unique test requirements and dedicated program objectives. The utilization of these systems on various aircraft simultaneously operating in enroute, terminal or approach airspace has been a developing problem throughout the last decade ("over 27,000 systems sold"). The FAA's concern over this developing problem resulted in the establishment of a Navigation Support Program in the early 1970's. The concern is first due to the fact that the unique combination of sensor errors, processing and filtering errors, flight technical errors and total system errors for each navigation system determines the amount of protected airspace and obstacle clearance required to insure safety. The second reason for concern is that these systems have been and are being certified without the 30 years of operational experience unique to the conventional VOR/DME navigation system and without having examined a comprehensive, global data base for each of these systems which could supplant the need for 30 years of operational experience.

The seriousness of this concern and the dire need for a thorough analysis of the system evaluation/certification/approval requirements can best be expressed by pointing out the "Catch 22" that is currently being experienced. As one user stated:

> "In the case of an ONS(Omega, ed.) already certified in commercial airline service, it was assumed that internal aspects of ONS design have already been proven via compliance with ARINC 599, RTCA DO-164 and FAA certification procedures. Specifically, it was assumed that the ONS navigational accuracy would be commensurate with the propagation prediction accuracy if it could be proved that signals were indeed being received and properly used".[5]

This example is typical of the expectations of most buyers and operators of advanced digital navigation systems. Yet this accuracy assumption is false. The same sophisticated operator recognizes the need for a comprehensive accuracy assessment when he states "In-flight measurement of these functions (signal tracking, station selection,

and estimation of navigation parameters) would more aptly be the subject of a formal technical evaluation and would require use of precision ground tracking radar (or equivalent), dedicated onboard instrumentation, and flights over a wide range of geographic locations". However, no such assessment has yet been completed* for the wide area coverage systems. No comprehensive data base exists and no quantitative evaluation of navigation accuracy exists for these systems. In this environment certification continues under the "buyer beware" philosophy by which the users are determining system suitability, system accuracy and system compatibility through operational experience.

The purpose of this current project is to rectify the existing situation and to determine and quantify error sources for the four generic navigation systems. Specific problems have been identified with the existing data which impact the general utility of the error budget data base. These problems are:

1) Incompatibility of the various "exiting" sets of data.
2) The lack of data for each navigation system on several aircraft types.
3) The incompleteness of geographic and meteorological variations in existing data bases for some systems.
4) Lack of substantive data for each system in each airspace region.

Development of error budget data for the navigation systems listed previously will include consideration of:

1) What existing data is suitable for error budget analysis?

*NOTE: The FAA Technical Center in Atlantic City, N.J. has undertaken such a program in the Systems Test and Evaluation Division (ACT-100). The results of their Navigation Program under ACT-100B will be relied upon and referenced heavily throughout this interim report. However, this program is not yet complete.

2) How should error budget data be used in certification?
3) What are the relative merits of alternative error combination techniques?

The answers to each of these three questions will vary for each navigation system under study. Of primary concern will be the interrelationships between navigation system accuracy and airspace limits (enroute, terminal, approach) and navigation system accuracy and vehicle characteristics (air transport, general aviation, helicopter, simulator, etc.). The current program will be limited to quantifying error sources for each navigation system, vehicle type, and airspace region combination either previously tested or to be tested in the near future. This task will serve to identify both the validity of existing data and the possible need for specific types of additional data.

3.1 ERROR BUDGET QUANTITIES

As previously stated, each of the previous researchers or project managers of separate but closely related navigation system test and evaluation programs has had a tendency to collect, analyze and present their data in slightly different terms. This presents a major correlation problem when attempting to integrate the quantitative results of several studies to establish a single comprehensive portrayal of the real world situation. Perhaps the most difficult task is the interpretation of the various error quantities which have been measured. Although statistics for total error are generally easy to interpret, different researchers often define the various total error components in different terms. For the purposes of this study navigation errors have been broken down into a total of seven error quantities shown in Table 3.1.

Of primary importance to this task is an understanding of the interrelationships between the error parameters which have been defined and the necessity for including them in an error budget analysis. This understanding is essential to the efficient collection of additional data in this program.

Table 3.1 Navigation System Error Components

ERROR QUANTITY	ERROR COMPONENT ORIENTATION	
	CROSSTRACK	ALONGTRACK
1. Total System Error	X	X
2. Navigation System Error	X	X
3. Sensor Error	X	X
4. Computer Error	X	X
5. Flight Technical Error	X	Not Applicable
6. Course Selection Error*	X	Not Applicable
7. Procedural or Blunder Errors	X	Not Applicable
*NOTE: For those Systems Requiring a Course Selection Input Via a Card Type Omni-Bearing Selector		

3.1.1 Total System Error

Total System Error represents the net evaluation of navigation system accuracy which is present for any given set of error circumstances. It is generally broken into its crosstrack (TSCT) and alongtrack (TSAT) components. In the current ATC system, TSCT is the component most applicable to error budget criteria studies as it describes the actual displacement of the aircraft from desired flight path in the horizontal reference plane. This relates directly to route width requirements. As metering and spacing procedures (4D) are introduced into the ATC system, total system alongtrack error will become increasingly important to the error budget evaluation. Experience has shown that TSCT and TSAT are quite similar in character. Thus transition to the 4D ATC system should be relatively straightforward from the viewpoint of system accuracy criteria.

One additional method of total system error description is often used in navigation error discussions for wide area coverage systems, that is the establishment of northing and easting components. Instead of using aircraft track as the reference for component discription,

true north is used as the reference. Both methods have their respective strengths but the track reference method is much more meaningful when describing errors in a navigation system based upon radial and DME measurements from a single ground station, particularly when the aircraft is tracking directly towards the station. In this situation crosstrack errors relate to VOR radial measurements and alongtrack errors relate to DME distance measurement. In any system which does not involve station to station navigation, such as area navigation or wide area coverage systems, north reference methods become equally as meaningful as track reference methods. However, because this study is primarily comparative in nature, it is advantageous to use track oriented methods whenever feasible in order to include as much previously collected data as possible. For this reason all error components subsequently discussed are track oriented rather than north oriented.

3.1.2 Navigation System Errors

Navigation System Errors are those errors which are incurred prior to position information being displayed to the pilot and are generally described in crosstrack and alongtrack components. These errors are sometimes further subdivided into sensor errors and computational errors. Sensor errors are those errors which are caused by irregularities in the navigation signal prior to reception in the aircraft such as propagation variances, VOR scalloping, multi-path errors, Loran-C geometric dilution of position, and low signal to noise ratios. Computation errors are those errors which are incurred by the airborne avionics equipment during signal processing. Advanced avionics systems which use multi-sensor algorithms or scanning techniques are capable of counteracting existing sensor errors with what are termed computation "errors", but which are filtering techniques intentionally introduced to decrease overall navigation system errors:

3.1.3 Pilot Errors

There are three error parameters which fall into the category of pilot or operator errors:

1) Flight Technical Error (FTE)
2) Course Selection Error
3) Blunders and/or Procedural Error

FTE is a measure of the indicated amount of deviation of the aircraft from the desired course in the horizontal reference plane. It can be caused by a variety of factors, most of which relate to pilot workload levels or judgment. FTE can be quantified by measuring and recording deflections of the Crosstrack Deviation Indicator (CDI). Typical FTE contributors include inattentiveness, cockpit distractions, noisy position display, basic display system design, lack of confidence in the displayed position, level of proficiency, and lack of understanding of the navigation system. Specific FTE values are closely related to the individual operator and to the signal providing the position display. Because of this, individual differences and system differences are major considerations in the data analysis efforts. All peripheral factors being equal, FTE values should remain relatively consistent for avionics systems of a given type (e.g. Loran-C) and of equal automation capability. In those geographic areas where signal anomalies create weak or intermittent navigation signals, erosion of confidence in the navigation equipment can be expected, with a resulting increase in FTE. FTE value can also be expected to increase whenever the avionics model becomes "noisy" due either to signal irregularities or to airborne computation equipment algorithms. This is due to the pilot flying a constant median track, based on historical flying habits, rather than attempting to precisely track a fluctuating Course Deviation Indicator. A "noisy" position display will also lead to confidence erosion which may be present even after the display becomes more stable.

The final contributor to FTE which will be discussed is system understanding. As most pilots have been trained in VOR/DME procedures and continue to use them on a daily basis, they will relate much more efficiently to VOR/DME systems than to any other system regardless of the level of proficiency training to which they are subjected. Thus it should be expected that FTE value may be somewhat lower for those

more intuitively understood system. Given an adequate level of operational experience, however, these differences should be minimized.

The next operator related error parameter is Course Selection Error (CSE). This is simply the physical displacement difference between the actual course setting and the desired setting. This error does not apply to those avionics systems which automatically establish the desired course. For more basic electromechanical systems the magnitude of CSE is approximately ±1.6° from the desired setting (95% confidence level).[4] A digital display (either mechanical or computerized) of the set course can significantly decrease CSE errors.

Blunders and/or procedural errors constitute a relatively minor portion of any given flight, but their impact is far greater than the frequency of their occurrence. Undetected blunders can be a serious hazard to flight, particularly in congested airspace. In reality, blunders are simply human errors which remain undetected to the extent that an artificially defined barrier (such as route width) is exceeded. Because this barrier is generally *experimentally* set at air corridor limits of ±4 nautical miles (enroute) each blunder constitutes a airspace violation. Thus although not entirely quantifiably integral with other error values such as FTE or TSCT, blunders remain an important aspect of error budget studies. Automation generally helps to decrease the overall occurrence of blunders and thus the implementation of some type of data link system should reduce blunder occurrences caused by pilot input errors. Because of their magnitude and their potential for creating separation problems, they will continue to be an object of interest to researchers investigating the error budget criteria needed to establish route width requirements in congested airspace.

All three of these operator related error parameters have a common idiosyncrasy in that they are usually only evaluated in a crosstrack direction. Given the nature of airspace corridor boundaries this is to be expected in the case of blunder errors. CSE errors are primarily associated with manually set courses used to fly inbound to or outbound from a navigation station waypoint. Thus CSE errors actually constitute angular crosstrack errors with no meaningful alongtrack components.

Similarly, alongtrack FTE is a concept which only applies at climb or descent points and possibly marginally at turn points. Thus, as a general rule, there are no alongtrack operator related error components applicable to today's avionics or airspace system. With the implementation of metering and spacing and a 4D airspace system, alongtrack deviations will begin to assume added importance necessitating the requirement to collect alongtrack operator related error data.

3.2 ADVANCED NAVIGATION SYSTEMS AND REQUIREMENTS

Having reviewed the need for further definition of system accuracy and error budgets, and having defined the error quantities of interest, it is now necessary to determine, in detail, which types of navigation systems need to be evaluated and what performance requirements are to be used. Table 3.2 presents a representative list of available advanced navigation systems. The systems listed in Table 3.2 have been subdivided into three broad system categories:

1) Systems Using Reference Facility For Continuous Navigation
2) Systems Using VOR/DME Information From Other Than The Reference Facility
3) Systems Not Using VOR/DME For Navigation

These categories are the three used for system compliance criteria specification in AC90-45A. Within each of these three categories, the types of systems have been classified into the appropriate user group — general aviation, commuter/business or air carrier. The systems listed under each user class are representative of the types currently available (and certified, except for the GPS Z-set). This is not a comprehensive shopping list of current systems but rather the first step in developing the data matrix of systems of interest vs systems for which error budget data has been collected. The reasons for developing Table 3.2 were to make the points that: (1) There are three broad categories from an accuracy compliance viewpoint, (2) There are at least three user classes which have different system requirements and system capabilities, and as there are, at the very least, four or

Table 3.2 Advanced Navigation Systems By Type and User Group

VOR/DME-RNAV SYSTEMS					
Systems Using Reference Facility For Continuous Navigation			Systems Using VOR/DME Information From Other Than The Reference Facility		
General Aviation	Commuter/ Business	Air Carrier	General Aviation	Commuter/ Business	Air Carrier
KN-74 AD-511/612 Cessna 400/800	KNS-80 KNC-610 ANS-31 NCP-2040 DAC 2000/7000	Could Buy Commuter/ Business Systems	Not Appli- able	Could Buy Air Carrier Systems	AIRNAV-300B ANS-70A TERN-100
WIDE AREA COVERAGE RNAV SYSTEMS (Systems Not Using VOR/DME for Navigation)					
General Aviation	Commuter/ Business	Air Carrier			
TDL-711	ONI-7000	TDL-424	Loran-C		
TI 9100			Loran-C		
	CMA-771/734	Same as Commuter/ Business Systems	Omega/VLF		
	LRN-70/80/85		Omega		
	GNS-500A		Omega/VLF		
	ONS-25		Omega		
	LTN-211		Omega/VLF		
	ONS-VII		Omega		
Z-Set	Z-Set	Z-Set	GPS		

more different types of navigation system implementation concepts represented (and being used in the NAS) for each user class.

The next step in developing the need for error budget data requires an examination of the AC90-45A compliance categories and accuracy requirements in greater detail. This is necessary to determine what airspace regimes must be tested for a system certification assessment.

The acceptable means of compliance for demonstrating capabilities as an area navigation system suitable for NAS operations are given

in FAA Advisory Circular 90-45A, Appendix A, Section 2[1]. This advisory circular section is further subdivided into accuracy requirements (2.a), system design requirements (2.b), equipment installation specifications (2.c), and flight manual information requirements (2.d). The error budget data to be analyzed is primarily applicable to the accuracy requirement. Therefore, in order to understand the need for specific data analysis techniques, the accuracy requirements for 2D navigation system of Appendix A Section 2.a of AC 90-45A are reproduced in their entirety.

2/21/75 AC 90-45A Appendix A Paragraph 2.a

A. ACCEPTABLE MEANS OF COMPLIANCE (FOR USE UNDER INSTRUMENT FLIGHT RULES)

An acceptable means of compliance with Section -.1301, -.1309, -.1431, and -.1581, of Part 23, 25, 27 or 29 (as applicable), with respect to area navigation systems, provided for use under IFR conditions, is to satisfy the critieria set forth in this paragraph.

a. Accuracy.

(1) 2-D RNAV System using Reference Facility for continuous navigation information. The total of the error contributions of the airborne equipment (receivers plus area navigation - including desired track setting as well as waypoint setting errors) when combined RSS with the following specific error contributions should not exceed the error values shown in Table 1, Appendix A.

VOR ground station	*±1.9°*
DME ground station	*±0.1 NM*

(2) 2-D RNAV systems which use VOR/DME information from other than the Reference Facilities must show that the algorithm used will always select a station that will provide crosstrack/alongtrack errors equal to or less than the greater of the RNAV system errors of the reference facility for any RNAV track (Table 1) or the errors shown in paragraph 2.a. (3).

***(3) 2-D RNAV System not using VOR/DME for continuous navigation information. The total of the error contributions of the airborne equipment (including update, aircraft position and computational errors), when combined with appropriate flight technical errors listed in 2.a(4) below, should not exceed the following with 95% confidence (2-sigma) over a period of time equal to the update cycle:*

***NOTE: While the non-VOR/DME error values quoted herein are correct from AC90-45A, they do not represent the current thinking of RTCA's SC-137.[4] The proposed RTCA changes will be evaluated and possibly included in the final version of this report.*

	Crosstrack	*Alongtrack**
Enroute	*2.5 nm*	*1.5 nm*
Terminal	*1.5 nm*	*1.1 nm*
Approach	*0.6 nm*	*0.3 nm*

(4) 2-D Flight Technical Errors (FTE) when combined RSS with errors discussed in (1) and/or (a) above determine the Total System error. The Total System error is used by airspace planners and includes the following specific FTE values for determining crosstrack position accuracies. Values larger than these must be offset by corresponding reduction in other system errors (see Appendix C). No FTE is used in determining the alongtrack accuracy.

Enroute	*±2.0 nm*
Terminal	*±1.0 nm*
Approach	*±0.5 nm*

**NOTE: Although there is no track keeping accuracy requirement in the along track direction for 2D RNAV systems or any pilot display of along track deviation for 2D systems, these error budget values for enroute, terminal and approach are airborne system error requirements without considering the FTE values from paragraph 2.a. (4).*

Several data acquisition requirements evolve upon thorough examination of these AC 90-45A accuracy requirements. First, total system error in both the crosstrack and alongtrack dimensions must be quantified. Second, the error contributions of the "airborne equipment" must be measured. (Airborne equipment error includes errors in navigation signals, e.g, Loran-C position, due to transmission and propagation-induced signal errors). Finally, the value of Flight Technical Error (FTE) must be measured. Upon satisfactorily instrumenting and recording these parameters the procedures of AC 90-45A Appendix C can be used to combine the error elements into an acceptable error budget. These procedures are based on the assumption that the variable errors from each of the error sources are normally distributed and independent. In this case, the errors may be combined in RSS (root-sum-square) fashion in order to demonstrate compliance. That is, the standard deviations, $_{\text{FTE}}$ and $_{\text{Airborne Equipment}}$ may be combined by taking the square root of the sum of the squares:

$$\sigma_{\substack{\text{Total}\\ \text{System}}} = \sqrt{\sigma^2_{\text{FTE}} + \sigma^2_{\substack{\text{Airborne}\\ \text{Equipment}}}} \qquad \text{(a)}$$

Using this recommended equation and rearranging terms, the implied budget for airborne equipment may be calculated from the values for total system error and FTE listed in Appendix A of AC 90-45A. That is,

$$\sigma_{\substack{\text{Airborne}\\\text{Equipment}}} = \sqrt{\sigma^2_{\substack{\text{Total}\\\text{System}}} - \sigma^2_{\text{FTE}}} \qquad \text{(b)}$$

The resulting values for the demonstration of compliance of the airborne navigation equipment have been calculated. These are:

AIRBORNE EQUIPMENT ERRORS

	Crosstrack	Alongtrack
Enroute	1.5 nm	1.5
Terminal	1.1 nm	1.1
Approach	0.3 nm	0.3

As previously noted, the airborne equipment error budget inherently includes errors in position due to signal transmission and propagation errors. The airborne equipment error budget, in addition, includes all signal filtering, processing, computational, output and display errors associated with the airborne navigation system. Also, as pointed out in the footnote on the alongtrack error budget of AC 90-45A, Appendix A, paragraph 2.a (4), the airborne equipment error budget values correspond to the crosstrack error budget values of paragraph 2.a. (3) with the FTE substracted as shown in equation (b).

This methodology will be used to compare and evaluate the error budget navigation system data from an AC 90-45A and NAS compatability viewpoint.

At this point we have defined the need for navigation system accuracy data and error budget data for three broad categories of system types, three different user groups (widely varying operational requirements) and three airspace regions. The remaining variable of importance for the error budget data base is the vehicle type. Vehicle performance characteristics and limits will have a major impact on system performance within the NAS. In fact, the vastly varying capabilities from the wide-body or "heavy" jets to the business executive helicopter can have an overriding influence on navigation system capability and system accuracy. For example, both total system

error and flight technical error would differ by an order of magnitude when flying VOR/DME-RNAV in the presence of VOR signal scalloping for the DC-10 vs the S-76. This is due to the fact that the DC-10 is not as highly maneuverable as the helicopter and would probably "fly through" the scalloping region in a heading hold mode while the attentive helicopter pilot could easily track the scallop. In the case of the DC-10, the total system error would be small and relatively constant for the duration of the scallop but FTE would be large in direct proportion to the magnitude of the scallop (noisey needle syndrome). For the helicopter tracking the scallop, the CDI needle would remain close to centered (very small FTE) while the total system error would become abnormally large for the scalloping region. Similar error budget differences occur due to vehicle performance capabilities when developing error budget data for LORAN-C, Omega or GPS. For this reason, the analysis of system accuracies, error budgets and certification data must include a range of test vehicles.

In summary, the detailed needs for advanced navigation system error budget data and the requirements which the data must satisfy have been reviewed in this section. As an aid in understanding the interrelationships between these requirements and in order to provide a focus for the data analysis to be performed subsequently, Table 3.3 was created. This table summarizes elements of the error budget problem in matrix form. Table 3.3 shows that, starting with the three broad categories or types* of navigation system defined in AC90-45A, a comprehensive approach to the error budget and system performance assessment would include data from at least 15 navigation systems (of varying cost, complexity and performance), eight different aircraft

*/NOTE/ The AC90-45A navigation system types include:

Type(1) 2-D RNAV System using Reference Facility for continuous navigation information."

Type(2) 2-D RNAV systems which use VOR/DME information from other than the Reference Facilities."

Type(3) 2-D RNAV system not using VOR/DME for continuous navigation information."

Table 3.3 Desired Error Budget Data Matrix

NAVIGATION SYSTEMS		ERROR BUDGET ELEMENTS											
		Total System Errors			Flight Technical Errors			Computer Errors			Sensor Errors		
	Airspace Regions	ENRT	TERM	APPR	ENRT	TERM	APPR	ENRT	TERM	APPR	ENRT	TERM	APPR
	Data Sources User - Aircraft Type												
Type (1) System A System B	Air Carrier - L1011 - DC-9												
Type(1) System B System B System C	Commuter/Business - Citation II - DHC-7 - Cessna 402												
Type(1) System C System D System E	General Aviation - Piper Seneca - Cessna 210 - S76												
Type(2) System F System F	Air Carrier - L1011 - DC-9												
Type(2) System G System G System H	Commuter/Business - Citation II - DHC-7 - Cessna 402												
Type(2) System H System I System J	General Aviation - Piper Seneca - Cessna 210 - S76												
Type(3) System K System K	Air Carrier - L1011 - DC-9												
Type(3) System L System L System M	Commuter/Business - Citation II - DHC-7 - Cessna 402												
Type(3) System M System N System O	General Aviation - Piper Seneca - Cessna 210 - S76												

types (representative of three diverse user profiles and system needs) and three airspace regions. In addition, Table 3.3 shows that as a minimum, the four error budget elements must be obtained for each system/user/aircraft/airspace region combination. If the desired data matrix shown in Table 3.3 were collected as a part of a comprehensive navigation system assessment program, then there would be a viable, analytically sound and statistically meaningful foundation upon which to make certification approval judgements, VOR/DME replacement system decisions, ATC computer enhancement requirements assessments and operational suitability determinations. However, this approach has not been taken due to the practical constraints of time, manpower and funding availability in the R&D community. Therefore, the remainder of this report will analyze what systems have been tested, what data was taken in what aircraft and which airspace regions were included. By reviewing the available data from previous uncoordinated (from an error budget viewpoint) and dissimilar (considering test objectives, flight path geometery, etc.) tests, an evaluation of the state-of-the-art in error budgets and system accuracy assessments can be made. This effort will comprise the remainder of this report.

3.3 REVIEW OF EXISTING ERROR BUDGET DATA

The detailed data availability and applicability review performed as one task of this study is summarized in this section. Due to the number and diversity of test programs analyzed, it was not feasible to review each programs objectives, flight paths, data collection matrices, etc. For this pertinent, but somewhat qualitative data, the reader must refer to the published reports listed in the reference for each system. The presentation in this section will provide quantitative data and analyze that data for relative system performance and compatiblity in the NAS.

As an index to the remainder of this discussion, Table 3.4 was prepared. Examination of this table shows that six performing agencies have been primarily responsible for the error budget data collected to date. First and foremost of this group of researchers is the FAA's Technical Center located in Atlantic City, New Jersey. The Navigation

Table 3.4 Summary of Existing Navigation System Data

System Tested	Performance Agency	Aircraft Type	User Category	Airspace Regions Evaluated			Reference Number
				Enroute	Terminal	Approach	
A. VOR/DME RNAV							
1. Collins ANS-70A	FAA Technical Center	Gulfstream G-1	Air Carrier		✓	✓	6
2. Delco R130A	United Airlines	Douglas DC-10	Air Carrier	✓	✓	✓	11
3. Litton LTN-104	FAA Technical Center	Boeing B-727	Air Carrier	✓	✓		11
4. EDO TCE-71A	FAA Technical Center	Gulfstream G-1	Commuter/ Business	✓	✓	✓	8
5. Air Data AD-611D	FAA Technical Center	Aero Comm AC-680	General Aviation		✓	✓	9
6. Butler VAC/ADD	FAA Technical Center	Gulfstream G-1	General Aviation	✓	✓	✓	10
7. King KN-74	Systems Control	Aero Comm AC-500	General Aviation	✓	✓	✓	11
B. LORAN-C							
1. Teledyne TDL-424							
a. Atlantic City	U.S. Coast Guard	Helicopter HH-52	Commuter/ Business	✓	✓	✓	12
b. Northeast Corridor	U.S. Coast Guard	Helicopter HH-52	Commuter/ Business	✓	✓	✓	12
c. Gulf of Mexico	U.S. Coast Guard	Helicopter HH-52	Commuter/ Business	✓			12
2. Teledyne TDL-711							
a. Northeast Corridor	FAA Technical Center	Helicopter CH-53	Air Carrier	✓			14,15
b. Gulf of Mexico	FAA Technical Center	Convair CV580	Commuter/ Business	✓			16
c. Baltimore Canyon	FAA Technical Center	Helicopter CH-53	Air Carrier	✓			14
d. West Coast	Systems Control	Piper Aztec D	General Aviation			✓	17
e. Vermont	DOT Transportation Systems Center	Beech Twin Bonanza	General Aviation			✓	22
C. OMEGA-OMEGA/VLF							
1. Litton LTN-211							
a. CONUS	U.S. Navy	Douglas A-3 & Lockheed P-3	Air Carrier	✓	NOT APPLICABLE		5
b. CONUS	Eastern Airlines	Boeing 727	Air Carrier	✓			Not Available
2. Can.Marc.CMA-734							
a. CONUS	Canadian Marconi	Cessna 421	Commuter/ Business	✓			18
b. Northeast Corridor	FAA Technical Center	Helicopter CH-53	Air Carrier	✓			Not Available

Program of the Technical Center has been underway since the early 1970's. The data collected, analyzed and published during this time period accounts for over 50% of the total data base analyzed. As shown in Table 3.4, this data collection effort has covered the gamut including VOR/DME RNAV (5 systems tested in 3 different aircraft), Loran-C (TDL-711 tested in both helicopters and fixed wing aircraft) and Omega (CMA-734 tested in a CH-53). The Technical Center is currently testing a GPS Z-set but the data is not yet complete or available.

In the VOR/DME-RNAV data base, two other groups have contributed. United Airlines provided enroute data using a Delco R130A system in their DC-10 aircraft. Systems Control Technology, Inc. (formerly Systems Control, Inc. (Vt.)) performed enroute, terminal area and approach testing of the King KN-74 system in an Aero Commander 500.

In the wide area coverage system test and evaluation, two Loran-C systems and two Omega/VLF systems have been evaluated. These are the Teledyne TDL-711 and TDL-424 Loran-C units and the Litton LTN-211 and Canadian Marconi CMA-734.

The U.S. Coast Guard combined with the FAA Technical Center has provided the bulk of the Loran-C data. This data was supplemented by the West Coast tests performed by Systems Control Technology, Inc.

Finally, the U.S. Navy, Canadian Marconi and the Technical Center have provided inputs to the Omega data base.

The data from all of the preceding sources was analyzed for usefulness in this error budget analysis. In particular, the data was categorized by error types measured, airspace regions tested and the previously defined Type(1), (2) or (3) navigation system categories.

3.3.1 Error Budget Data for Type(1) Navigation Systems

The first data to be presented will be the VOR/DME-RNAV data applicable to the Type(1) category. This data includes the following mix of navigation system/aircraft types:

Navigation System		Aircraft Used	
Collins	ANS-70A	Gulfstream	G-1
Delco	R130A	Douglas	DC-10
Litton	LTN-104	Boeing	B-727
EDO	TCE-71A	Gulfstream	G-1
Foster Air Data	AD-611	Aero Commander	AC-680
Butler	VAC/ADD	Gulfstream	G-1
King	KN-74	Aero Commander	AC-500

The data for these systems were reported in References 6-11. These references were used to aggregate data for the four error budget elements:

Total System Error
Flight Technical Error
Computer Error
Sensor Error

Where data was available, errors were quantified for enroute, terminal and final approach airspace. In addition, where applicable, the errors were further divided into crosstrack and alongtrack components for direct comparison with the AC90-45A approval criteria. The results of this analysis are presented in Table 3.5. All of the values listed in Table 3.5 are in nautical miles and all are for manually flown flight segments. Autopilot data is available from the references.

The data in Table 3.5 was further subdivided by user category. As shown in the table the air carrier and general aviation data consisted of three navigation systems each while only a single commuter/business category system was tested.

In the air carrier group, the Delco R130A and the Litton LTN-104 provided enroute and terminal results while the Collins ANS-70A provided terminal and approach results. Also, as shown in the table, the ANS-70A and the R130A provided data for all four error budget elements while the LTN-104 data was limited to total system error and flight technical error quantities. In general, the air carrier data presented in Table 3.5 meets all of the approval criteria presented in

Table 3.5 Error Budget Data Summary For Type (1)* Systems
(All Values in Nautical Miles)

NAVIGATION SYSTEMS			Total System Errors			Flight Technical Errors			Computer Errors			Sensor Errors		
NA = Not Available			ERROR BUDGET ELEMENTS**											
Airspace Regions			ENRT	TERM	APPR	ENRT	TERM	APPR	ENRT	TERM	APPR	ENRT	TERM	APPR
CT=Crosstrack / AT=Alongtrack			CT / AT	CT / AT	CT / AT	CT	CT	CT	CT / AT	CT / AT	CT / AT	CT / AT	CT / AT	CT / AT
Air Carrier:														
ANS-70A	Gulfstream	G-1	NA / NA	.72 / NA	.47 / NA	NA	.30	.18	NA / NA	.80 / .60	.44 / .56	NA / NA	1.0 / .62	.44 / .68
R130A	Douglas	DC-10	.55 / NA	.48 / NA	.47 / NA	.73	.48	NA	.78 / NA	.46 / NA	NA / NA	NA / NA	.40 / NA	NA / NA
LTN-104	Boeing	B-727	.75 / NA	.75 / NA	NA / NA	.22	.21	NA	NA / NA	NA / NA	NA / NA	NA / NA	NA / NA	NA / NA
Commuter/Business:														
TCE-71A	Gulfstream	G-1	2.8 / NA	.92 / NA	.50 / NA	1.34	1.08	.38	1.65 / 1.65	.73 / .55	.29 / .43	2.8 / .18	.91 / .75	.46 / .39
General Aviation:														
AD-611	Aero Comm	680	NA / NA	1.53 / NA	.47 / NA	NA	1.07	.35	NA / NA	1.34 / 1.01	.34 / NA	NA / NA	.67 / .39	.26 / NA
VAC/ADD	Gulfstream	G-1	.98 / NA	1.19 / 1.35	NA / NA	.82	.68	.56	NA /	1.40 / 1.2	NA / NA	NA / NA	1.39 / .49	NA / NA
KN-74	Aero Comm	500	2.23 / NA	1.50 / NA	.47 / NA	1.05	1.54	.49	NA / NA	1.99 / NA	.858 / NA	NA / NA	1.36 / NA	.34 / NA

/NOTE/*Type I = Systems Using VOR/DME Reference Facility for Continuous Navigation

**All Data Manually Flown

Section 3.2 for Type (1) systems. None of the air carrier total system errors exceeded 1.0 nm. Average values of 0.65 nm (enroute), 0.66 nm (terminal) and 0.47 nm (approach) were obtained. Similarly, the FTE data obtained on these systems was acceptably small. In general, the sensor errors (ground and airborne equipment/signal errors) tend to drive the computer (computational filtering, or weighting) errors. In fact Reference 11 has shown a statistically reliable negative correlation between sensor and computer errors for this class of system. When this occurs, it simply indicates that the navigation system is performing as designed and cancelling received random or bias errors through its filtering algorithm (Kalman filter or other sensor weighting techniques). This fact can be verified by noting, for example in Table 3.5, during terminal testing of the ANS-70A, sensor error was 1.0 nm, computer error was 0.8 nm and yet the FTE was only 0.3 nm indicating that the navigation system output to the pilot's display (CDI) was smooth enough to allow him to fly more accurately than the raw data.

The EDO TCE-71A was the only representative commuter/business system for which error budget information was obtained. This system was tested in the Gulfstream G-1 by the FAA Technical Center. Data was collected for all three airspace regions and for all four error quantities. As was the case for the air carrier systems, the Commuter/Business category system's data, in general, satisfied the current AC90-45A approval criteria. However, the data shown for enroute navigation in Table 3.5 and the detailed analysis performed shows some interesting system characteristics. The following error quantities from Table 3.5 are important:

Total System Error	2.8 nm
Sensor Error	2.8 nm
Computer Error	1.65 nm

This enroute data was taken at two different cruising altitudes — 10,000 ft and 20,000 ft. The combined result of 2.8 nm Total System Error is within AC90-45A criteria, but due to the large change from the air carrier value of 0.65 nm it was investigated further. As previously discussed, with adequate signal filtering or computational

weighting the impact of large sensor errors on Total System Errors can be minimized. Obviously, this did not occur for the system tested, since the 2.8 nm Sensor Error showed up directly in the Total System Error. The predominant factor which caused variation in the results for the sensor error was the geometry of the flight tests. Higher tangent point distances (TPD) and alongtrack distances (Figure 3.1 shows definitions for TPD and ATD) resulted in higher sensor errors.

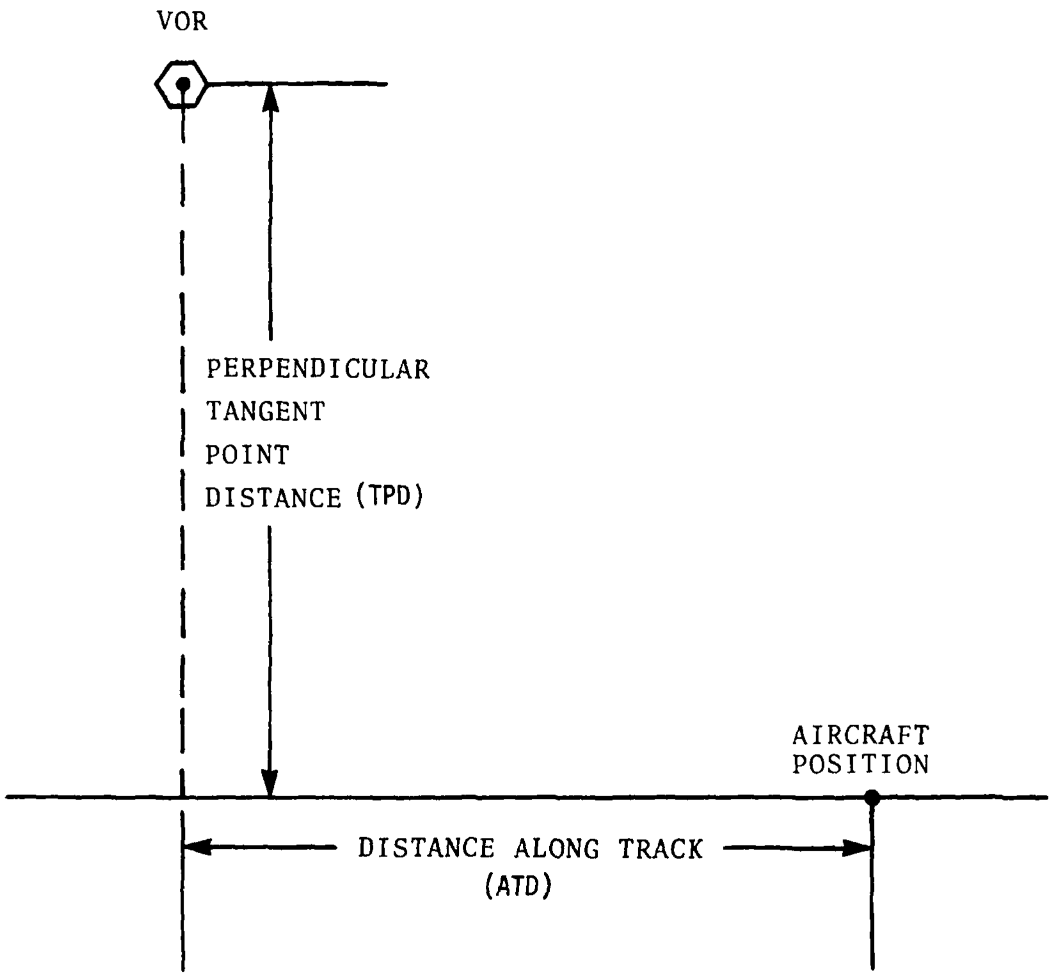


Figure 3.1 Definition of Tangent Point and Alongtrack Distances

Table 3.6 shows the effect of the geometry on the sensor crosstrack and sensor alongtrack errors. The column labeled VOR Standard Deviation lists the values reported in Report No. FAA-RD-76-113, "An Analysis of Radio Navigation Sensor Accuracies Associated with Area Navigation." The Geometric Index (GI) column in Table 3.6 lists a value which indirectly represents the TPD and ATD for each category of data. The GI was computed by averaging the distance between each waypoint/ground station pair which was utilized for the data collection in each category. The predicted one sigma value for sensor crosstrack error listed in Table 3.6 was computed by taking the product of the sine of the VOR one sigma value times the GI. The predicted value was very close to the measured sensor crosstrack error in each data category.

The 10,000 ft enroute data exhibited a relatively low one sigma value for VOR error (1°) and a correspondingly low value for measured sensor crosstrack error. However, the geometry of the 20-25000 ft experiment produced a GI of 59.4, the highest value in the table. Corresponding to this geometry was a large predicted sensor crosstrack error and finally a large measured sensor crosstrack error. It was this geometry then which lead to the Total System Error of 2.8 nm enroute which was significantly larger than the air carrier data. It should be noted that this type of phenomenon is precisely the reason why comparison of single error numbers is not sufficient to demonstrate compliance. The dynamics of error interactions must somehow be considered, documented and accounted for.

As shown in Table 3.6, no such problems occurred in the terminal or approach GI's. Therefore, the measured error quantities for Total System, FTE, Computer and Sensor errors were correspondingly reduced for these two airspace regions.

The General Aviation error budget data in Table 3.5 was collected using three representative navigation systems — the Foster Air Data AD-611, the Butler VAC/ADD and the King KN-74. Data for all four error quantities and all three airspace regions was collected. In general, the data from all three systems was comparable for each airspace region when a specific error quantity is examined. The General Aviation systems

Table 3.6 Comparative Study of Sensor Errors[8]

Data Category	VOR Standard Deviation (degrees)	Geometric Index (nmi)	Predicted One Sigma Sensor Crosstrack Error (nmi)	SNCT One Sigma (nmi)	SNAT One Sigma (nmi)
A2 Approaches (Collocated VOR)	1.5	3.2	0.084	0.149	0.063
Other Approaches	1.5	16.7	0.437	0.333	0.347
Terminal Area	1.7	17.8	0.528	0.456	0.377
En Route 10,000 ft	1.0	42.6	0.743	0.845	0.234
En Route 20-25,000 ft	1.6	59.4	1.659	1.472	1.029

tested satisfied the AC90-45A approval criteria for Type (1) Systems. In the enroute and terminal flight regimes, these systems performed within a 1.0 to 2.25 nm Total System Error which is quite acceptable considering they represent the low end of the VOR/DME-RNAV system spectrum from both cost and performance viewpoints. FTE, Computer Errors and Sensor Errors were similarly within specified limits.

In summary, review of the available data for Type (1) navigation systems has shown that the Total System performance to be expected was always less than or equal to the following values:

	AIRSPACE REGIONS		
User Category	Enroute	Terminal	Approach
Air Carrier	0.75 nm	0.75 nm	0.5 nm
Commuter/Business	3.0 nm	1.0 nm	0.5 nm
General Aviation	3.0 nm	1.6 nm	0.5 nm

It should be noted that these values represent upper limits on Total System Errors experienced for all navigation systems and aircraft types tested. These numbers are not the statistical aggregation of data from each test weighted by the number of samples for each test. From an analytical viewpoint the performance indicated by these upper limits is sufficient to examine the acceptability or unacceptability of the data base for Type (1) systems. Although this data base was not of the precise breadth and depth indicated as "desirable" in Table 3.3, it was collected on a sufficient variety of systems, using comparable routes, adequate data collection and reduction and it utilized a sufficient number of representative aircraft types. Therefore, the VOR/DME-RNAV data base presented in Table 3.5 should provide sufficient information to compare to the wide area coverage system performance of Loran-C and Omega.

3.3.2 Error Budget Data for Wide Area Coverage Navigation Systems

As previously indicated, the accuracy requirements for Loran-C, Omega, Omega/VLF and GPS based navigation systems are described in AC90-45A under Type (3). These requirements are as follows:

	Total System Error Crosstrack	Total System Error Alongtrack	FTE (Crosstrack only)
Enroute	2.5 nm	1.5 nm	2.0 nm
Terminal	1.5 nm	1.1 nm	1.0 nm
Approach	0.6 nm	0.3 nm	0.5 nm

These requirements are somewhat more stringent than the those for Type (1) Systems as previously discussed in Section 3.2. As derived in that section, they result in Airborne Equipment Error limits of 1.5 nm enroute, 1.1 nm terminal and 0.3 nm approach for both the alongtrack and crosstrack direction. These values, however, represent the current approval criteria and will be used for comparison with error budget data.

Table 3.7 was compiled from References 5, and 12-18. The data shown in Table 3.7 represents the most meaningful set of error budget statistics currently available. All of the data in the table was developed from uncalibrated, two sigma data either available in published form or obtained through the FAA Technical Monitor for this contract.

The first observation to be made regarding Table 3.7 is that the data base for Loran-C and Omega-Omega/VLF is not nearly as comprehensive compared to either the VOR/DME RNAV data base or the Desired data base. As shown in the table, only two Loran-C systems have been tested and they are both from the same manufacturer. In the case of Omega-Omega/VLF, two different manufacturers equipment were tested. However, both the Litton LTN-211 and the Canadian Marconi, CMA734 are Omega/VLF systems. Essentially, the error budget data shown in Table 3.7 is representative of a general aviation Loran-C (TDL-711) and three air carrier quality wide area systems (TDL-424, LTN-211 and CMA-734).

The second important observation regarding the wide area coverage data base is that even for those systems tested, the amount of data for each of the error quantities is extremely limited. This is expecially true for FTE, computer errors and sensor errors. Other than the TDL-424 tests performed by the U.S. Coast Guard and planned, collected and analyzed by Systems Control Technology, Inc.[12,13], the right 3/4 of the table is blank.

Table 3.7 Error Budget Data Summary For Wide Area Coverage Navigation Systems (Uncalibrated, 2σ Data in Nautical Miles unless otherwise indicated)

CT = Crosstrack
AT = Alongtrack
NA = Not Available

NAVIGATION SYSTEMS / Airspace Regions	ERROR BUDGET ELEMENTS: Total System Errors			Flight Technical Errors			Computer Errors			Sensor Errors		
	ENRT	TERM	APPR	ENRT	TERM	APPR	ENRT	TERM	APPR	ENRT	TERM	APPR
	CT / AT	CT / AT	CT / AT	CT	CT	CT	CT / AT	CT / AT	CT / AT	CT / AT	CT / AT	CT / AT
LORAN-C												
1. TDL-424, HH-52												
a. Atlantic City	.56	.51	.10	.12	.15	.09	.57	.49	.04			
b. Northeast Corridor	.60	.70	.50	.19	.24	.32	.58 / .69	.66	.42			
c. Gulf of Mexico*	.25											
2. TDL-711, CH-53												
a. Northeast Corridor**	.50											
b. Baltimore Canyon**	1.07	0.78	0.55									
3. TDL-711, CV-580												
Gulf of Mexico***	.81 / .83											
4. TDL-711, Piper Aztec												
West Coast			.50			.36			.30 / .08			.46 / .72
5. TDL-711, Beech Twin Bonanza												
Vermont												
OMEGA-OMEGA/VLF												
1. LTN-211, A3,PE****	1.5	NOT APPLICABLE			NOT APPLICABLE			NOT APPLICABLE			NOT APPLICABLE	
2. CMA-734, Cessna 421	1.8 / 1.4											
3. CMA-734, CH-53**												

* 2drms data only
** Preliminary data report not yet published
*** Calibrated mode only
**** CEP data only (1.5 CEP @50th percentile, 4.1 CEP projection at 95th percentile)

On the positive side (left ½), Table 3.7 shows that as far as Loran-C testing is concerned, four important geographic areas have been operationally tested. These are:

1) The Northeast including the Washington, D.C.-New York-Boston corridor, the Baltimore Canyon (N.J. Offshore) and Atlantic City.
2) The Gulf of Mexico
3) The West Coast-Lake Tahoe, CA, Klamath Falls, OR, Grand Junction, CO and Reno, NV.
4) State of Vermont

The other positive aspect of Table 3.7 is that it illustrates that for these four geographic areas, Loran-C is basically a 1.0 nm or better accuracy system in enroute airspace. That is, the TDL-424 and TDL-711 data taken with helicopters had Total System Errors of 0.50 to 1.07 nm for these areas. This data was in the uncalibrated mode. The Gulf of Mexico data for the Convair 580 shown in Table 3.7 was in the calibrated mode. Comparable statistics in the Gulf of Mexico with Loran-C uncalibrated were:

Total System Crosstrack Error = 3.5 nm[16]
Total System Alongtrack Error = 2.7 nm[16]

The dearth of FTE data for wide area coverage navigation systems has already been mentioned. Table 3.7 shows that there is none for Omega or Omega/VLF, the TDL-711 data is limited from Vermont and the West Coast in approach only. There is no TDL-711 enroute or terminal FTE. However, it should be noted that for the TDL-424, tested in a helicopter (HH-52) the enroute, terminal and approach FTE was very small (i.e. considerably less than 0.5 nm throughout). Similarly, the approach data from the West Coast tests of the TDL-711 showed FTE to be only 0.36 nm. This area is certainly worthy of further investigation since AC90-45A allows error budgets which are considerably higher. The reason for this improvement in FTE compared to VOR/DME navigation relates directly to the signal quality and steadiness. It appears that for those geographic locations tested (Northeast Corridor, Atlantic City the West Coast and the State of Vermont), that Loran-C offers an improvement over VOR/DME-RNAV from a FTE viewpoint. Data in other aircraft and

at a variety of locations is needed to build a case for this improvement.

The computer errors (crosstrack and alongtrack) shown for the TDL-424 tests are also small (0.04 nm - 0.69 nm). For this particular data set, computer errors included all airborne equipment errors from the receiver through the computer and the displays. This was a peculiarity of the data reduction process. However, it was not easy to add another error category to Table 3.7 so these values were listed as shown. Where the sensor and computer errors have been broken out, as for the TDL-711 on the West Coast, they are also shown to be less than 0.75 nm and comparable to the TDL-424 combined airborne equipment results.

The Omega — Omega/VLF test results shown in Table 3.7 are limited to enroute only. That is, these systems are not designed for or currently used for terminal area or approach navigation. Even so, the results available for these systems from an error budget viewpoint are inadequate. The only viable data collection attempt from an accuracy viewpoint was performed by Canadian Marconi to demonstrate compliance with AC90-45A. This data showed that the CMA-734 could satisfy the current criteria and that Omega when designed to operate in a primary relative mode rather than in the hyperbolic mode can satisfy the 2.5 nm crosstrack and 1.5 nm alongtrack approval criteria.

The test data required to demonstrate this capability included 40 flying hours and 5975 nautical miles of data collection. The test pattern (circuit) essentially flew the east coast of the U.S. in a southerly direction, traversed westward across the southern states, flew the west coast in a northerly direction and then flew east across the northern states. The detailed data obtained are shown in Table 3.8.

Table 3.8 Omega/VLF Accuracy Data From CMA-734 Certification Testing

	Mean Error (nm)	Standard Deviation (nm)	Mean + 2X Standard Deviation (nm)
Alongtrack Accuracy	0.074	0.679	1.433
Crosstrack Accuracy	0.210	0.872	1.765

In summary, the review of wide area coverage (Type (3)) navigation system error budget data has determined a severe deficiency for the type of data needed. This data includes more systems (TI-9000, ONI-7000 Loran-C units; GNS-500, ONS-25, LTN-3000, Omega Units, etc.), additional terminal/approach data for Loran-C and enroute data for Omega-Omega/VLF and most importantly, a definition and quantification of all the error budget quantities especially FTE. The importance of the FTE error budget element will be discussed in depth during evaluation of the RSS error combination technique (Section 4.0).

3.4 ERROR BUDGET DATA ANALYSIS

This section will utilize the SC-137 MOPS Dynamic Test Criteria and compare VOR/DME RNAV Dynamic Results to the MOPS Criteria. The dynamic tests performed include:

1. Dynamic Response
2. Turn Anticipation
3. Waypoint or Leg Sequencing
4. Direct-To Function

These tests were performed by a SCT developed fast-time computer simulator of an RNAV equipped aircraft piloted by manual or autopilot control responses. The VOR/DME signal simulator, which is integral to the fast-time RNAV simulator, provided VOR bias errors, DME ground and airborne errors, and scalloping reflector errors. This fast-time simulator is also capable of simulating Loran-C, RNAV equipped aircraft. Loran-C dynamic results are not included due to lack of time.

3.4.1 Dynamic Test Conditions

Presented in Figures 3.2 through 3.7 are the test flight paths recommended by SC-137 in Section 2.5.3 of Reference 4. These figures were developed from Tables 2.2 and 2.3, which also specify test conditions. (Criteria for Figure 3.7 is shown on the figure only.)

The flight paths for the Dynamic Response tests were flown in the enroute mode (1.0 nm per CDI dot deflection) and in the approach mode (0.25 nm per dot deflection) as specified in Table 2.2. The purpose of the test is to show that the crosstrack and alongtrack errors do not

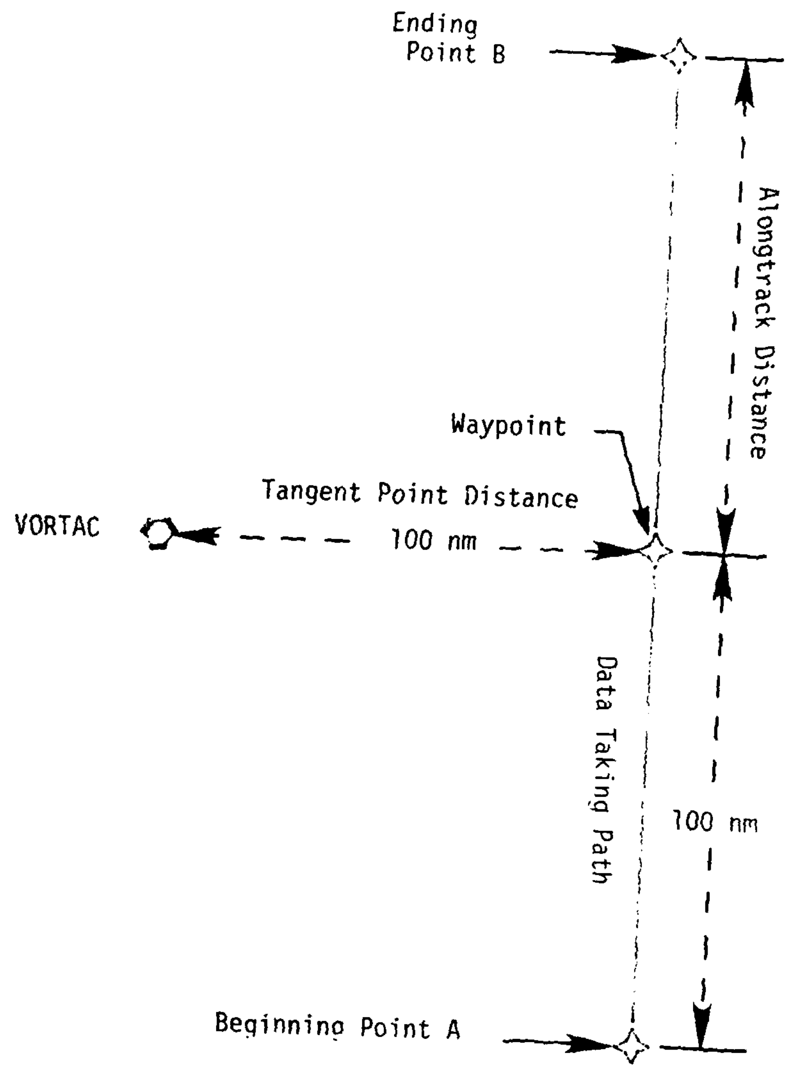


Figure 3.2 Dynamic Test Flight Path: Test Numbers I and II; Enroute Mode

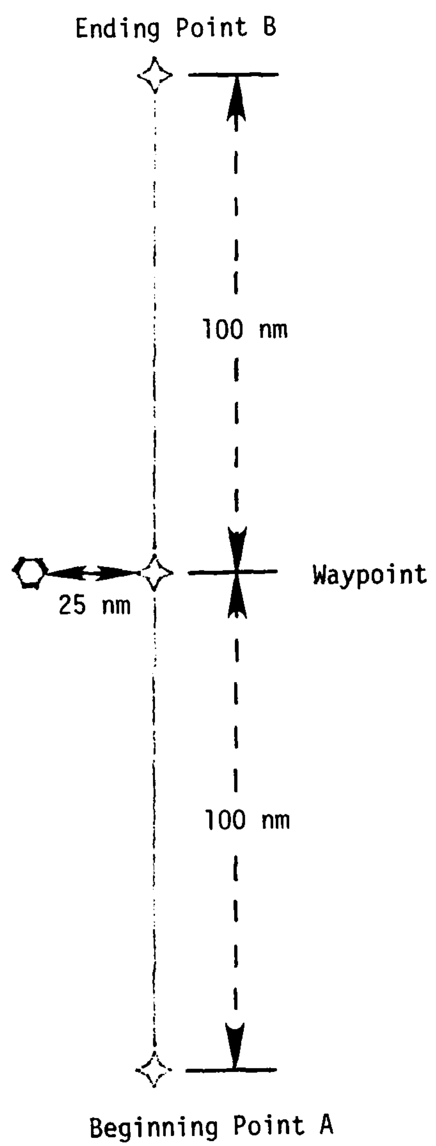


Figure 3.3 Dynamic Test Flight Path: Test Numbers III, IV, V; Enroute and Approach Modes

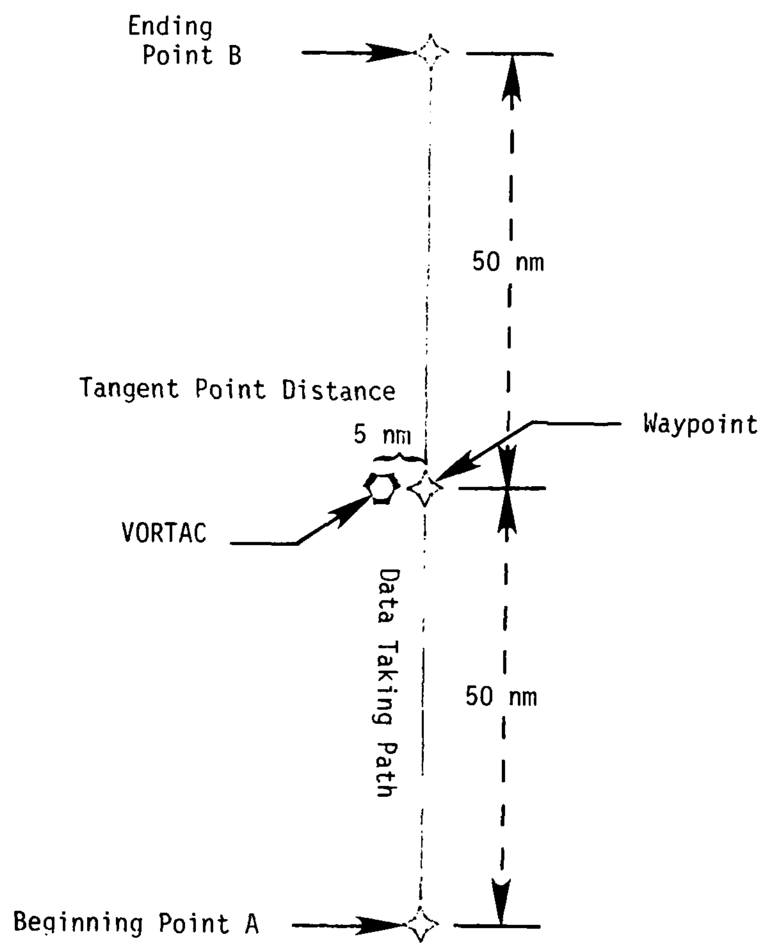


Figure 3.4 Dynamic Test Flight Path: Test Number VI, VII, VIII; Enroute Mode

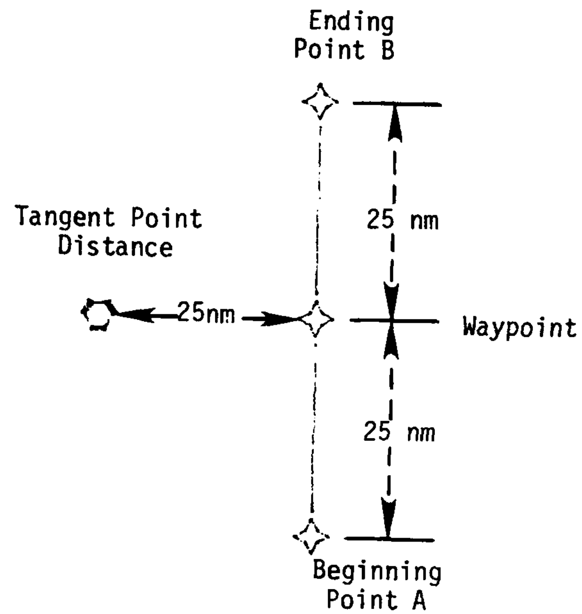


Figure 3.5 Dynamic Test Flight Path: Test Numbers IX and X; Approach Mode

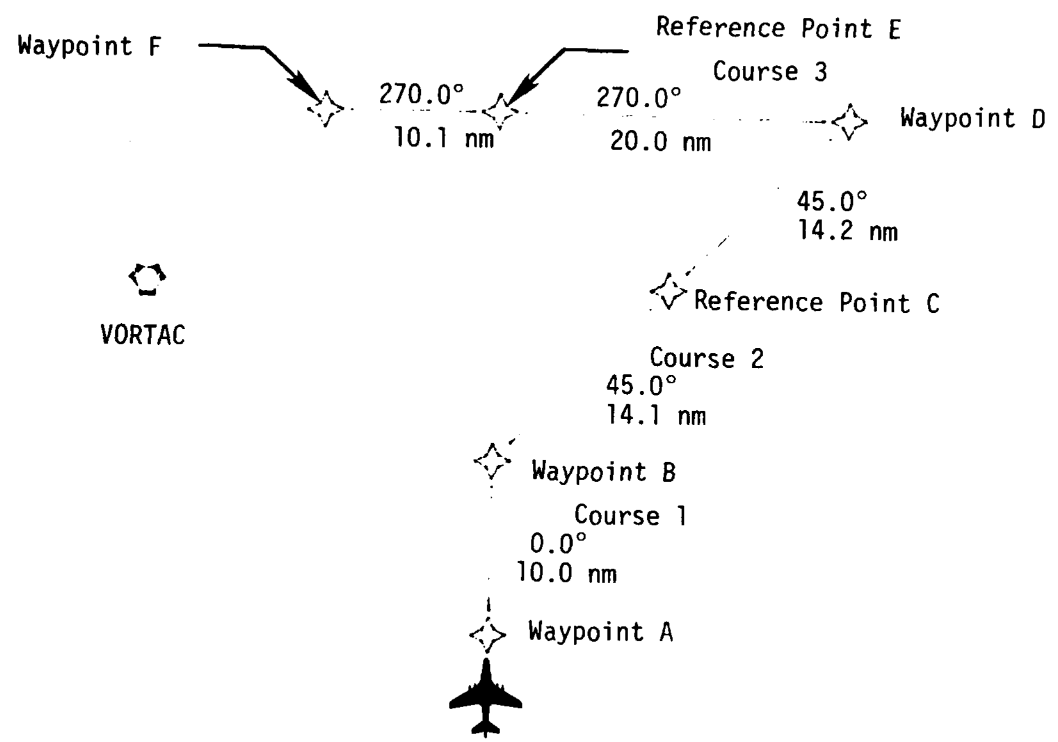
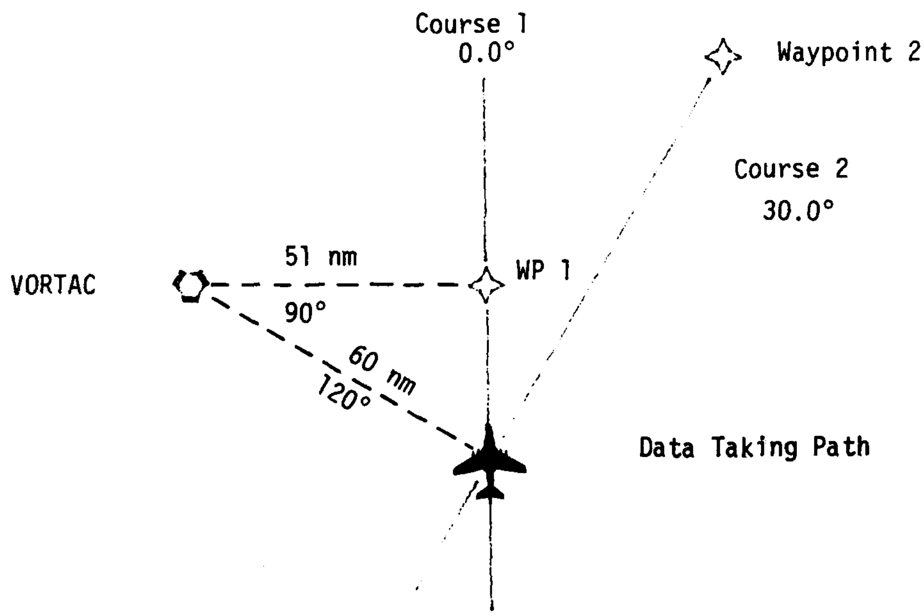


Figure 3.6 Multiple-Leg Dynamic Test Geometry For the Turn Anticipation and Direct-To Dynamic Test (Table 2.3)



Tangent Point Distance = 60 nm

Figure 3.7 Waypoint or Leg Sequencing and Response Time Test

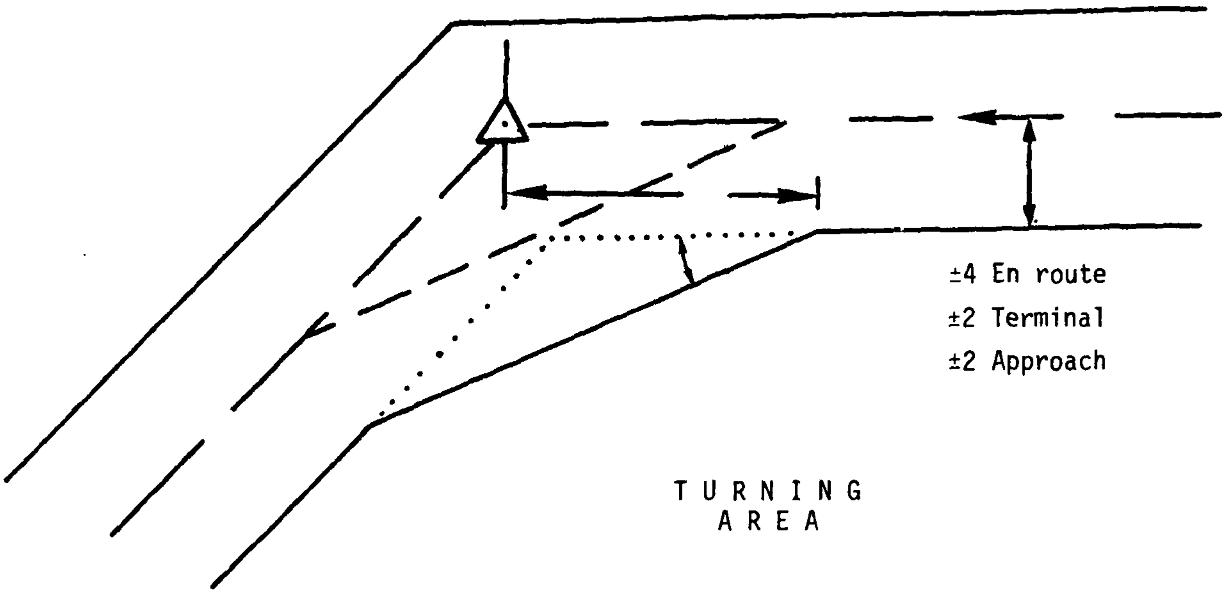
exceed the requirements of Table 3.9[4].

The Turn Anticipation test uses the route structure of Figure 3.6 for the specified conditions of Table 2.3, Test Numbers 1 and 2. The purpose of this test is to show that the RNAV equipment does not exceed the crosstrack and alongtrack error requirements of Table 3.9, or exceed the "corner cut" envelope described in Figure 3.8[4].

The Waypoint or Leg Sequencing test was flown using the specifications shown in Figure 3.7. This test requires the selection of waypoint 2 and course 2 after having settled on course 1. The RNAV unit is required to provide a centered crosstrack indication within the limits of Table 3.9 within five seconds.

The Direct-To Function test uses the route structure of Figure 3.6 and the test criteria from Table 2.3, Test Number 3. During this test, when reference point C is crossed, Waypoint F is selected as the active direct-to waypoint. The purpose is to show that the RNAV unit provides guidance so as not to "S" turn during transition to intercept.

Conditions for the signal error sources for all tests included a VOR bias error of 3.31° (RSS value of VOR ground and airborne error), a DME ground error of 0.10 nm and a DME airborne error of 0.20 nm plus one percent of actual distance from the VORTAC. To better simulate the real world, a scalloping reflector error was introduced in four tests (one in the Dynamic Response Test, two in the Turn Anticipation test, and one in the Waypoint or Leg Sequencing test). The scalloping reflector was positioned at 25 feet to the left of the VORTAC at an angle of 30° from true north. The scalloping error for the tests was valued at 2.5% of the direct VOR signal. Obviously, more than one scalloping reflector could be present at various locations with larger or smaller magnitudes of error reflected by each. As the aircraft transverses the radial paths of the VOR, the associated scalloping errors are received by the RNAV unit and provide erroneous guidance which induces the pilot to "chase the needle". This results in large crosstrack and alongtrack errors for both sensor and FTE. This is necessary area for further investigation with respect to providing a near real-world



1. Angle of splay for expanding area is ½ the amount of the course change.

2. Expansion for the "corner cutter" begins at:

   3 nm for Approach

   7 nm Enroute for equipment designed to operate below 350 kt.

   12 nm Enroute for equipment designed to operate above 350 kt.

NOTE: This test does not include crosstrack and alongtrack errors which are included in planned air route structures

Figure 3.8 "Corner Cut" Turn Expansion for Turn Anticipation Test [4]

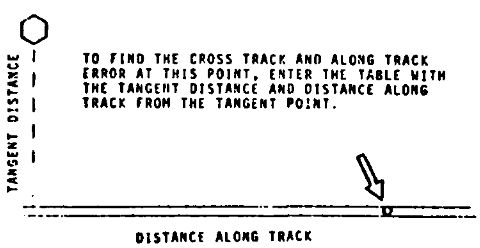
Table 3.9 VOR/DME RNAV Equipment Requirements Accuracy (95% Probability) [4]

DISTANCE ALONG TRACK FROM TANGENT POINT

(Rows: DISTANCE FROM TANGENT POINT TO VOR/DME)

		0	5	10	15	20	25	30	35	40	50	60	70	80	90	100	110	120	130
0	(XTRK)		0.6	0.8	1.1	1.4	1.7	2.0	2.3	2.6	3.2	3.9	4.5	5.2	5.8	6.4	7.1	7.7	8.4
	(ATRK)		0.6	0.6	0.6	0.6	0.7	0.7	0.8	0.8	0.9	1.0	1.0	1.1	1.2	1.3	1.4	1.5	1.6
5	(XTRK)	0.6	0.6	0.8	1.1	1.4	1.7	2.0	2.3	2.6	3.3	3.9	4.5	5.2	5.8	6.4	7.1	7.7	9.4
	(ATRK)	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.8	0.9	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7
10	(XTRK)	0.6	0.7	0.9	1.1	1.4	1.7	2.0	2.3	2.6	3.3	3.9	4.5	5.2	5.8	6.5	7.1	7.7	9.4
	(ATRK)	0.8	0.8	0.8	0.8	0.9	0.9	0.9	1.0	1.0	1.1	1.2	1.2	1.3	1.4	1.5	1.6	1.7	1.8
15	(XTRK)	0.6	0.7	0.9	1.1	1.4	1.7	2.0	2.3	2.6	3.3	3.9	4.5	5.2	5.8	6.5	7.1	7.7	8.4
	(ATRK)	1.0	1.0	1.0	1.1	1.1	1.1	1.2	1.2	1.2	1.3	1.4	1.4	1.5	1.6	1.7	1.7	1.8	1.9
20	(XTRK)	0.6	0.7	0.9	1.2	1.4	1.7	2.0	2.3	2.7	3.3	3.9	4.6	5.2	5.8	6.5	7.1	7.7	8.4
	(ATRK)	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.5	1.6	1.6	1.7	1.8	1.9	1.9	2.0	2.1
25	(XTRK)	0.7	0.8	1.0	1.2	1.5	1.8	2.1	2.4	2.7	3.3	3.9	4.6	5.2	5.8	6.5	7.1	7.9	8.4
	(ATRK)	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.7	1.7	1.7	1.8	1.9	1.9	2.0	2.1	2.1	2.2	2.3
30	(XTRK)	0.7	0.8	1.0	1.2	1.5	1.8	2.1	2.4	2.7	3.3	3.9	4.6	5.2	5.9	6.5	7.1	7.8	8.4
	(ATRK)	1.8	1.8	1.8	1.8	1.9	1.9	1.9	1.9	2.0	2.0	2.1	2.1	2.2	2.2	2.3	2.4	2.4	2.5
35	(XTRK)	0.8	0.8	1.0	1.3	1.5	1.8	2.1	2.4	2.7	3.3	4.0	4.6	5.2	5.9	6.5	7.1	7.8	8.4
	(ATRK)	2.1	2.1	2.1	2.1	2.1	2.2	2.2	2.2	2.2	2.3	2.3	2.4	2.4	2.5	2.5	2.6	2.7	2.7
40	(XTRK)	0.8	0.9	1.1	1.3	1.5	1.8	2.1	2.4	2.7	3.3	4.0	4.6	5.2	5.9	6.5	7.1	7.8	8.4
	(ATRK)	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.5	2.5	2.5	2.6	2.6	2.7	2.7	2.8	2.9	2.9	3.0
50	(XTRK)	0.9	1.0	1.1	1.3	1.6	1.9	2.2	2.5	2.8	3.4	4.0	4.6	5.3	5.9	6.5	7.2	7.8	8.4
	(ATRK)	2.9	2.9	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.1	3.1	3.2	3.2	3.3	3.3	3.4	3.4	3.5
60	(XTRK)	1.0	1.0	1.2	1.4	1.7	1.9	2.2	2.5	2.8	3.4	4.0	4.7	5.3	5.9	6.6	7.2	7.8	8.5
	(ATRK)	3.5	3.5	3.5	3.5	3.5	3.6	3.6	3.6	3.6	3.6	3.7	3.7	3.8	3.8	3.8	3.9	3.9	4.0
70	(XTRK)	1.0	1.1	1.3	1.5	1.7	2.0	2.3	2.6	2.9	3.5	4.1	4.7	5.3	6.0	6.6	7.2	7.9	8.5
	(ATRK)	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.2	4.2	4.2	4.2	4.3	4.3	4.4	4.4	4.4	4.5	4.5
80	(XTRK)	1.1	1.2	1.4	1.6	1.8	2.1	2.3	2.6	2.9	3.5	4.1	4.7	5.4	6.0	6.6	7.3	7.9	8.5
	(ATRK)	4.6	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.8	4.8	4.8	4.9	4.9	5.0	5.0	5.0	5.1
90	(XTRK)	1.2	1.3	1.4	1.6	1.9	2.1	2.4	2.7	3.0	3.5	4.2	4.8	5.4	6.0	6.7	7.3	7.9	9.6
	(ATRK)	5.2	5.2	5.2	5.2	5.3	5.3	5.3	5.3	5.3	5.3	5.4	5.4	5.4	5.5	5.5	5.5	5.6	5.6
100	(XTRK)	1.3	1.4	1.5	1.7	1.9	2.2	2.4	2.7	3.0	3.6	4.2	4.8	5.4	6.1	6.7	7.3	7.9	9.6
	(ATRK)	5.8	5.8	5.8	5.8	5.8	5.8	5.9	5.9	5.9	5.9	5.9	6.0	6.0	6.0	6.1	6.1	6.1	6.2
110	(XTRK)	1.4	1.5	1.6	1.8	2.0	2.3	2.5	2.8	3.1	3.6	4.2	4.9	5.5	6.1	6.7	7.3	8.0	8.6
	(ATRK)	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.5	6.5	6.5	6.5	6.6	6.6	6.6	6.7	6.7	6.7
120	(XTRK)	1.5	1.6	1.7	1.9	2.1	2.3	2.6	2.8	3.1	3.7	4.3	4.9	5.5	6.1	6.8	7.4	8.0	8.6
	(ATRK)	6.9	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.1	7.1	7.1	7.1	7.2	7.2	7.2	7.3	7.3
130	(XTRK)	1.6	1.7	1.8	2.0	2.2	2.4	2.6	2.9	3.2	3.7	4.3	4.9	5.6	6.2	6.8	7.4	9.0	8.7
	(ATRX)	7.5	7.5	7.5	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.7	7.7	7.7	7.7	7.8	7.8	7.8	7.9

NOTE: THE ABOVE TABLE IS A RESULT OF AN RSS COMBINATION OF THE FOLLOWING ERROR ELEMENTS:



TO FIND THE CROSS TRACK AND ALONG TRACK ERROR AT THIS POINT, ENTER THE TABLE WITH THE TANGENT DISTANCE AND DISTANCE ALONG TRACK FROM THE TANGENT POINT.

GROUND:
VOR 1.4°
DME 0.1 NM

AIRBORNE:
VOR 3.0°
DME 0.2 NM + 1.0%
CSE 1.6°

RNAV SYST 0.5 NM

FTE XTRK Zero
ATRK Zero

simulation. It would not be necessary and probably too cumbersome to model the locations of all scalloping reflectors at all VOR/DME sites. The other promising alternative is to model the characteristics of the power spectral density associated with the combination of all scalloping errors as an aircraft crosses VOR radials.

All simulated flights were conducted in the manual pilot mode. This was in lieu of the autopilot mode which often requires more airspace, particularly after a turn. This is a necessary area for investigation with respect to error budgeting.

Another condition used in every test, except the Waypoint or Leg Sequencing test, was turn anticipation. The simplified rule used for determining turn anticipation was one nm for every 100 kts of true airspeed (rounded to the nearest 100), i.e., at 180 kts. 2 nm of turn anticipation was used.

The final condition common to all tests was a steady 20 kt wind from NNE at 25°.

3.4.2 Analysis of Dynamic Test Results

There are certain results common to all of the tests performed. In these tests the aircraft's actual track begins at the designated beginning waypoint. From this point the aircraft's actual track is immediately driven right of the desired track. This occurs because the RNAV unit thinks that it is left of track due to a 3.31° VOR sensor bias error plus ground and airborne DME errors. Naturally, the VOR bias error contributes to crosstrack and alongtrack error throughout the flight. As the aircraft approaches the tangent point abeam the VOR, the crosstrack error approaches zero. Traveling away from the tangent point on a northerly course, the actual aircraft position is driven left of track. For the situations when the aircraft is on a westerly course (the Multiple Leg Test) and north of the VOR, the actual aircraft position is driven right of track. This geometry occurs only when VOR and DME errors are defined as positive. When they are negative, the reverse geometry would apply. Of course, VOR and DME errors can be any combination of positive and negative.

It should also be noted that the crosstrack and alongtrack accuracy requirements in Table 3.9, were computed based on zero FTE component. Although FTE is small in all tests, except for test with scalloping errors, FTE is an important component to airspace budgeting, particularly when air traffic controller procedures are involved.

Another similarity noted in the detailed analysis of the data is that the alongtrack errors tended to exceed Table 3.9 requirements by 0.1 to 0.9 nm, usually for alongtrack distances greater than 20 nm to the tangent point and for distances of 25 nm or more from the VOR to the tangent point. This occured only on segments south of the tangent point where DME alongtrack errors are positive when added to positive VOR alongtrack errors. On segments north of the tangent point, the alongtrack errors were significantly smaller, since the DME errors here are negative when added to positive VOR alongtrack errors. Although crosstrack and alongtrack errors exceed limits on a segment on one side of the tangent point, a statistical analysis should consider the mean error of both segments. This would, however, tend to show errors exceeding limits as smaller or even within limits.

The following paragraphs will discuss the summary results by each of the Dynamic Test categories: Dynamic Response, Turn Anticipation, Waypoint or Leg Sequencing, and Direct-To. Following this, each flight will be separately analyzed in detail.

Dynamic Response Test

There were twelve flights conducted to satisfy the ten corresponding tests described earlier in Table 2.2. Test Number III was flown both in approach and enroute sensitivity, and Test Number VII was reflown with scalloping errors. The purpose of the Dynamic Response Test is to demonstrate that crosstrack and alongtrack errors do not exceed Table 3.9 requirements for Figures 3.2-3.5. Ten flights did not exceed the AC-90-45A route width requirements. The two that exceeded were Test Number III and V. Both were flown in the enroute mode and with VOR/DME errors only. Test Number III was flown at 180 kts and Test Number V at 540 kts. Both flights exceeded route width requirements at the beginning of the flight where the RNAV unit directed the aircraft right of track, i.e., 7.3 nm for Test III and 6.6 nm for Test V. It may be argued correctly that much of that error is FTE, i.e., 2.2 nm for Test III and 2.3 nm for Test V. Nevertheless, this initial VOR/DME shift in track is relevant and comparable to changing guidance from

one VORTAC to another, and thereby, possibly exceeding airspace allowances.

Most of the flights were comparatively smooth except for Test VII with scalloping errors, where the aircraft tended to "chase the needle". It should be recognized that only one scalloping reflector was modeled in the simulator. More than one reflector would have a significant effect on possibly exceeding route width and Table 3.9 requirements.

As for Table 3.9 requirements, crosstrack errors only exceeded the limits by 0.1 to 0.2 nm at tangent point distances of 100 nm. The 25 and 5 nm tangent distance tests did not exceed crosstrack error requirements, except for Test VII with scalloping. Test VII had crosstrack errors exceeding limits by 0.1 to 0.7 nm at the farther distances alongtrack.

Alongtrack errors were exceeded for all tests with tangent point distances of 25 nm and 100 nm. The 100 nm tangent distance tests (I and II) showed the greatest excursions of 0.1 to 0.9 nm, and 0.1 to 0.6 nm for the 25 nm tangent point distance tests. Test VII with scalloping did not exceed alongtrack error limits, as did none of the other 5 nm tangent distance tests.

In summary, route width boundaries were only exeeded in two tests. For all tests without scalloping errors crosstrack errors exceeded Table 3.9 limits by only 0.2 nm. Alongtrack errors exceeded limits by as much as 0.9 nm. The test with scalloping errors showed the most frequency of crosstrack deviation exceeding limits by as much as 0.7 nm.

Turn Anticipation Test

The purpose of this test is to demonstrate that the crosstrack and alongtrack errors do not exceed Table 3.9 requirements with the multiple leg dynamic test conditions (Figure 3.6). Included in this purpose is to demonstrate that the method of turn anticipation of the RNAV equipment does not exceed the "corner cut" envelope previously described in Figure 3.8.

Four flights were conducted to satisfy the conditions of Table 2.3, Test I and II. For both tests, two flights were made, one with and one without scalloping errors. All tests stayed within AC-90-45A route width boundaries. The tests without scalloping errors did not exceed crosstrack error requirements of Table 3.9. Alongtrack errors were only exceeded by 0.1 nm on the leg from reference point A to waypoint B. Test I with scalloping errors exceeded crosstrack error limits by 0.4 nm only on the leg from waypoint B to waypoint D. Along-track errors were exceeded by 0.1 nm on leg A to B, and by 0.1 to 0.2 nm on leg B to D. Test II with scalloping exceeded crosstrack error limits by 0.1 to 0.4 nm on leg B to D, and by 0.1 to 0.3 nm on leg D to F. Alongtrack errors were exceeded by 0.1 nm only on leg A to B.

For the case of turn anticipation accuracy, at no time did the actual aircraft position exceed the corner cut envelope during each turn.

In summary, Tests I and II with scalloping errors are characterized by frequent crosstrack deviation, although turn anticipation airspace allowances were not violated. Crosstrack errors exceeded limits by a larger amount (0.4 nm) than alongtrack (0.2 nm). Test I and II without scalloping errors exhibited no significant errors. However, these tests do demonstrate the contribution that scalloping errors have in near real-world simulation.

Waypoint or Leg Sequencing and Response Time Test

The purpose of this test is to show that the RNAV unit will produce a centered crosstrack indication within the limits of Table 3.9 within the first five seconds after course 2 and waypoint 2 have been selected (Figure 3.7). This test is composed of two flights, one with and one without scalloping errors. The flight without scalloping errors produced a centered crosstrack indication within the first five seconds after waypoint 2 selection and within Table 3.9 requirements. Similarly, the flight with scalloping errors representing the near real world environment, showed a centered crosstrack indication within Table 3.9 limits and within the first five seconds after waypoint 2 selection. However, crosstrack errors exceeded Table 3.9 limits by 0.1 nm, and alongtrack errors exceeded

limits by 1.1 nm during the next six nm.

In summary, both flights performed within the prescribed error requirements for impromptu course and waypoint selection.

Direct-To Function Test

The purpose of this test was to demonstrate that the RNAV unit would not provide guidance in the form of an "S" turn during transition to intercept the leg of an active direct-to waypoint. This test was flown with the requirements defined in Test III of Table 2.3. No scalloping errors were used in this flight due to limited computer time sharing accessibility. There were no Table 3.9 requirements to meet with this test since it is only a functional test. As will be observed in the detailed analysis and plot, the RNAV equipment did not "S" turn in transition to the direct-to leg. However, it should be understood that turn anticipation was used in this test. Because of this, the RNAV unit projected its turning or anticipation waypoint 2 nm after the specified reference point C where the RNAV unit would have turned if there was no anticipation. Therefore, the leg to the direct-to waypoint and its associated airspace is shifted further north than the supposed or intended leg.

In summary, the RNAV equipment did not "S" turn during transition to the leg of the direct-to waypoint as required by the Direct-To Function Test.

The following pages of this section will detail the performance of each flight individually including a plot and table of results for each.

Dynamic Response Test Number I

The actual aircraft position begins at Point A, as shown in Figure 3.9, and is immediately driven right of track approximately five nautical miles (nm). This was caused in part by the RNAV unit receiving a 3.31° VOR sensor bias error causing it to think it was left of track. There was also an associated DME ground and airborne error of approximately 1.4 nm at the beginning of the flight. Together the VOR and DME errors produced a seven nm alongtrack error and a five nm crosstrack error in the first few miles of the flight.

During the flight the simulator provided near zero FTE navigation, with the crosstrack error approaching zero and about a six nm alongtrack error as the aircraft reached the tangent point distance (Waypoint). At the waypoint, VOR equaled 3.31° and DME equaled 1.0 nm.

Crossing the Waypoint and enroute to Point B, the 3.31° VOR bias error and the DME error drove the aircraft left of track. At the end of the flight, the crosstrack error was approximately seven nm left of track, and the alongtrack error was about five nm. The VOR error equaled 3.31° and the DME error equaled 1.4 nm.

Throughout the flight crosstrack errors were well within AC-90-45A requirements, however, alongtrack errors to the waypoint were larger by 0.1 to 0.9 as shown in Table 3.10.

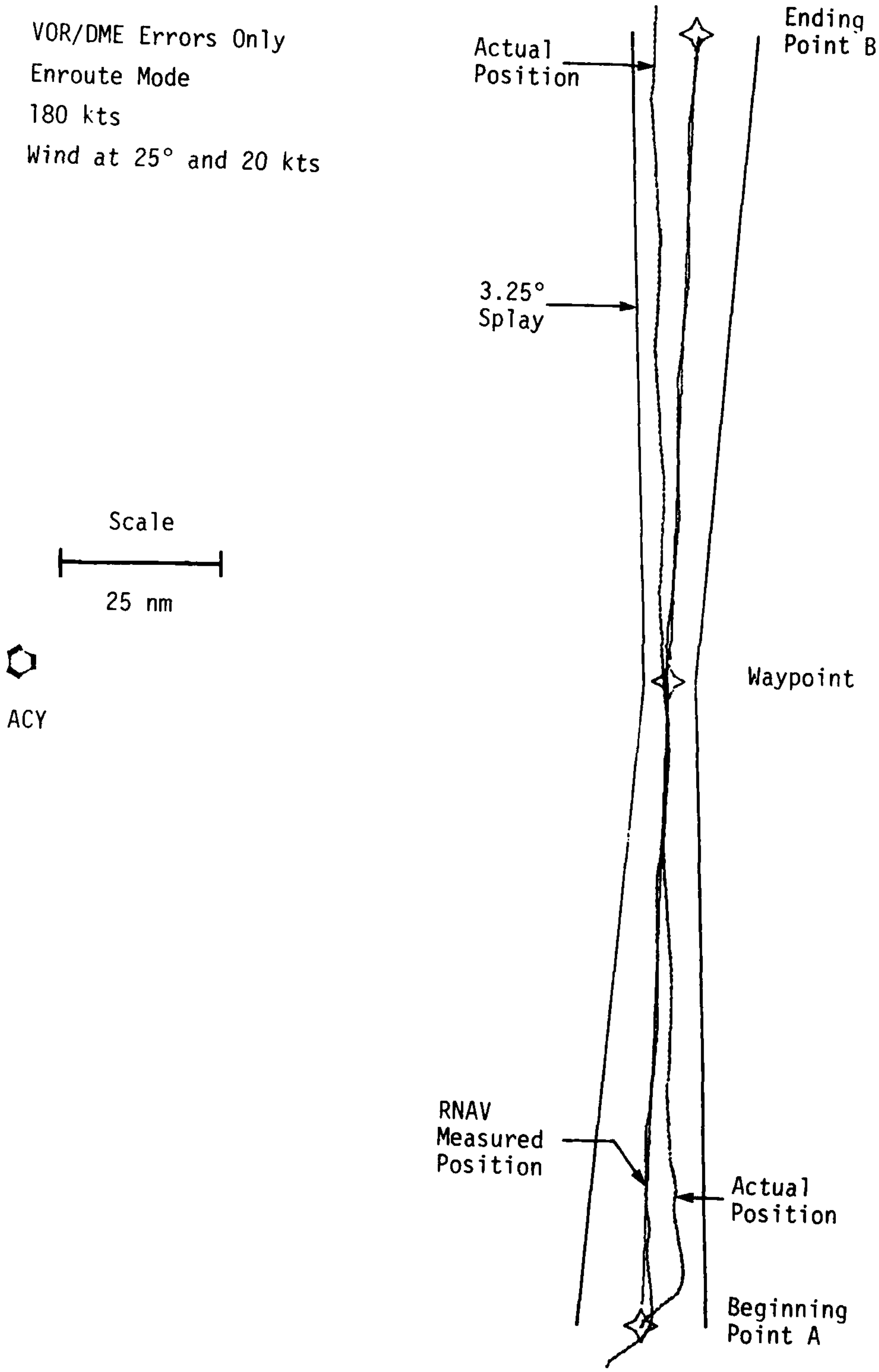


Figure 3.9 Dynamic Response Test Number I

Table 3.10 Dynamic Response Test
Number I

ALONGTRACK DISTANCE	TABLE 3.9**		SIMULATION			
	XTRK*	ATRK+	XTRK		ATRK	
			TO WAYPOINT	FROM WAYPOINT	TO WAYPOINT	FROM WAYPOINT
0	1.3	5.8	-0.9	-0.9	5.8	5.8
5	1.4	5.8	-0.6	-1.1	5.9	5.7
10	1.5	5.8	-0.2	-1.4	5.9	5.6
15	1.7	5.8	0.0	-1.7	6.0	5.6
20	1.9	5.9	0.3	-1.9	6.0	5.6
25	2.2	5.8	0.6	-2.3	6.1	5.5
30	2.4	5.9	0.9	-2.6	6.1	5.5
35	2.7	5.9	1.2	-2.9	6.2	5.4
40	3.0	5.9	1.5	-3.1	6.3	5.3
50	3.6	5.9	2.1	-3.7	6.4	5.2
60	4.2	5.9	2.6	-4.3	6.5	5.1
70	4.8	6.0	3.2	-4.9	6.6	5.0
80	5.4	6.0	3.8	-5.4	6.8	4.8
90	6.1	6.0	4.3	-6.0	6.9	4.7
100	6.7	6.1	5.0	-6.6	6.7	4.6

*XTRK is Crosstrack error limits
**Tangent Point Distance = 100 nm
+ ATRK is Alongtrack error limits

Dynamic Response Test Number II

This flight produced essentially the same VOR and DME errors as shown in Test I, and seen in Figure 3.10. The only observable difference is the RNAV unit in Test II required more time to acquire a centered crosstrack guidance than in Test I because of the greater airspeed (540 kts).

Crosstrack errors were within AC-90-45A limits as shown in Table 3.11. Alongtrack errors on the route to the tangent point distance waypoint were slightly larger than the A-90-45A limits by 0.1 to 0.9 nm.

Table 3.11 Dynamic Response Test Number II

ALONGTRACK DISTANCE	TABLE 3.9*		SIMULATION			
	XTRK	ATRK	XTRK		ATRK	
			TO WAYPOINT	FROM WAYPOINT	TO WAYPOINT	FROM WAYPOINT
0	1.3	5.8	-0.8	-0.8	5.8	5.8
5	1.4	5.8	-0.5	-1.2	5.9	5.8
10	1.5	5.8	-0.3	-1.4	5.9	5.7
15	1.7	5.8	0.0	-1.6	5.9	5.6
20	1.9	5.9	0.4	-2.0	6.0	5.5
25	2.2	5.8	0.7	-2.3	6.1	5.4
30	2.4	5.9	0.9	-2.5	6.1	5.4
35	2.7	5.9	1.2	-2.8	6.2	5.3
40	3.0	5.9	1.5	-3.1	6.3	5.3
50	3.6	5.9	2.0	-3.6	6.4	5.2
60	4.2	5.9	2.7	-4.3	6.6	5.1
70	4.8	6.0	3.2	-4.8	6.7	4.9
80	5.4	6.0	3.8	-5.5	6.9	4.8
90	6.1	6.0	4.4	-6.0	6.7	4.8
100	6.7	6.1	5.0	-6.6	6.7	4.5

*Tangent Point Distance = 100 nm

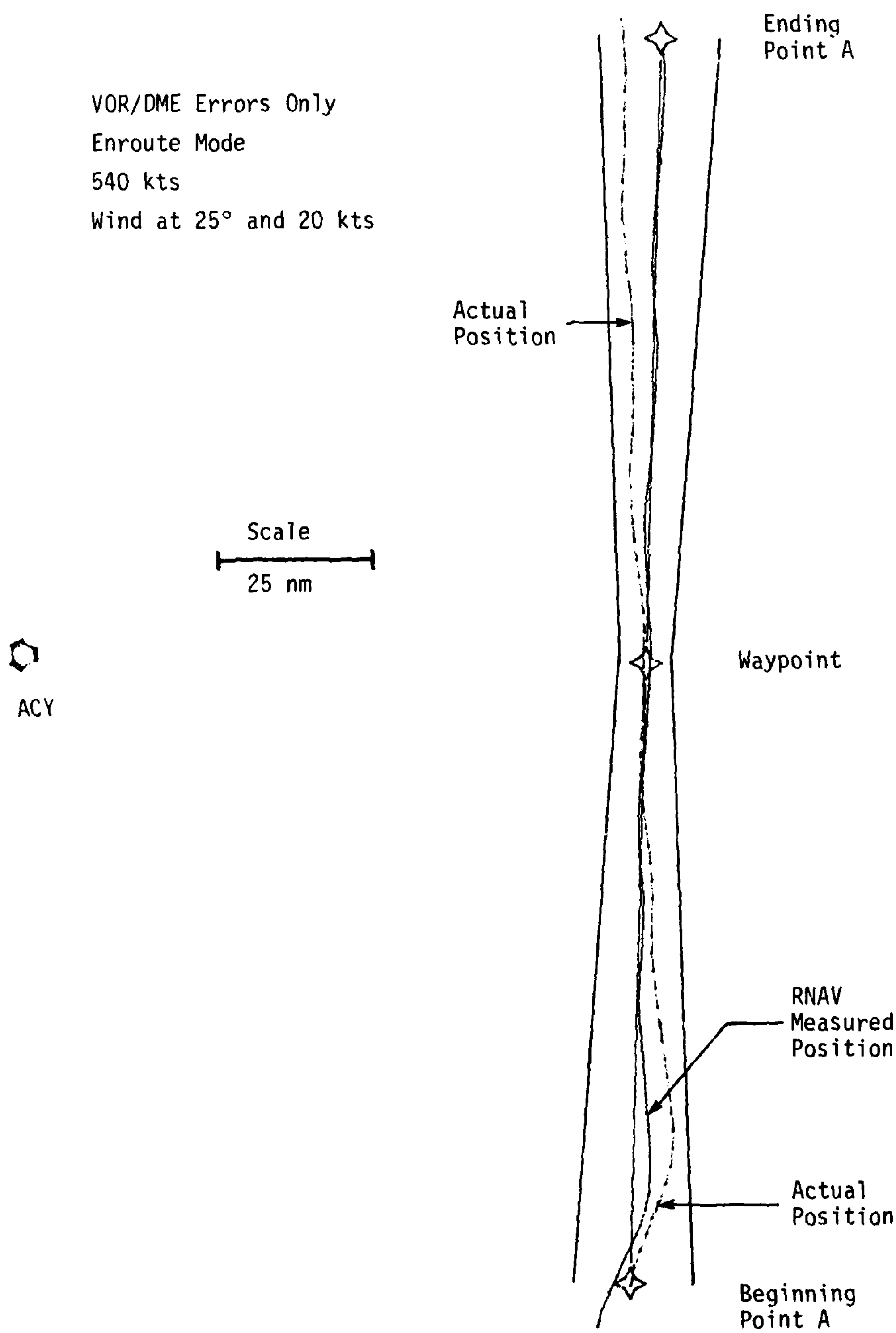


Figure 3.10 Dynamic Response Test Number II

Dynamic Response Test Number III

This test required two flights; one with approach sensitivity (0.25 nm per dot on the CDI) and one with enroute sensitivity (1.00 nm per dot), shown in Figures 3.11 and 3.12, respectively.

There are two distinct differences observed in the plots. First, the approach sensitivity flight is typical of more heading change corrections than with enroute sensitivity. Second, the initial guidance to center on track is slower with approach sensitivity than with enroute but there is also less overshot with approach sensitivity.

Both flights stayed within the AC-90-45A crosstrack error requirements shown in Tables 3.12 and 3.13. However, the alongtrack errors enroute to the tangent point waypoint were slightly larger by 0.1 to 0.3 nm for approach and 0.1 to 0.6 for enroute as shown in Tables 3.12 and 3.13. It should also be noted in the plot that the overshot at the beginning of the flight is due to an approximate 2.3 nm FTE right of track. This incident may indicate that TSCT errors associated with changing VORTAC, may not necessarily meet AC-90-45A airspace requirements.

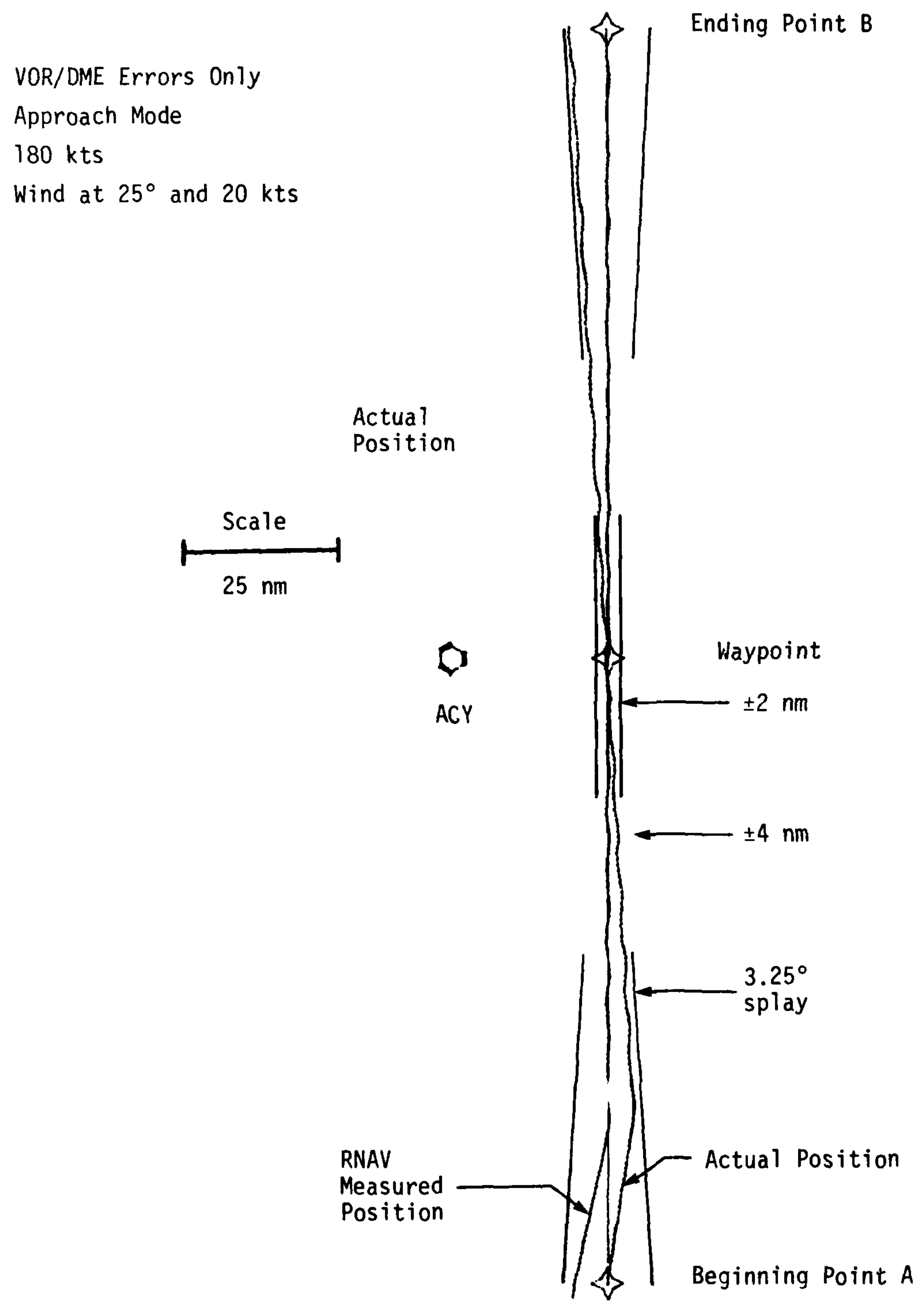


Figure 3.11 Dynamic Response Test Number III with Approach Sensitivity

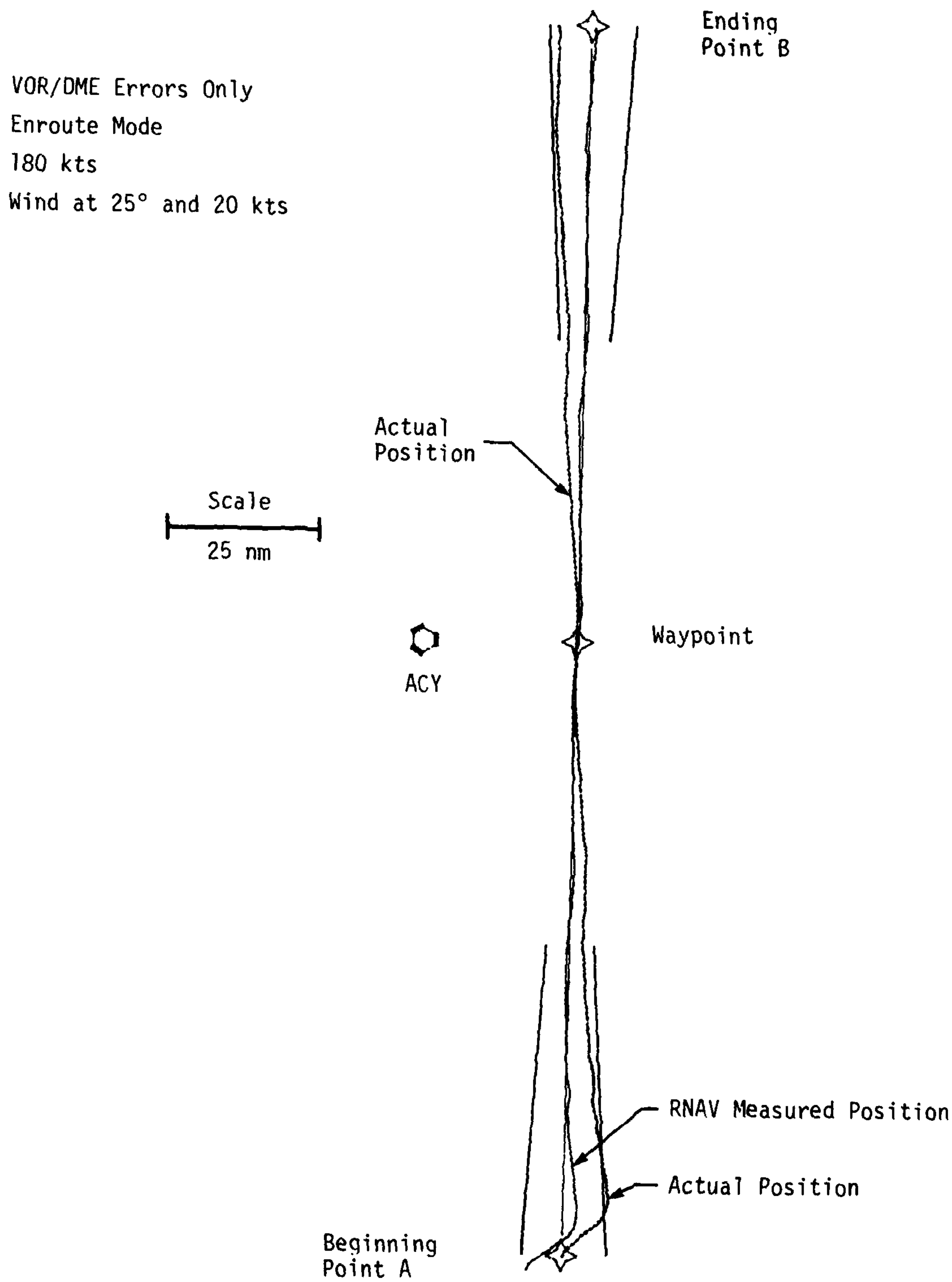


Figure 3.12 Dynamic Response Test Number III With Enroute Sensitivity

Table 3.12 Dynamic Response Test Number III With Approach Sensitivity

ALONGTRACK DISTANCE	TABLE 3.9*		SIMULATION			
	XTRK	ATRK	XTRK		ATRK	
			TO WAYPOINT	FROM WAYPOINT	TO WAYPOINT	FROM WAYPOINT
0	0.7	1.5	-0.2	-0.2	1.5	1.5
5	0.8	1.5	0.0	-0.5	1.5	1.4
10	1.0	1.6	0.4	-0.8	1.6	1.3
15	1.2	1.6	0.6	-1.1	1.6	1.3
20	1.5	1.6	0.9	-1.4	1.7	1.2
25	1.8	1.6	1.2	-1.7	1.8	1.2
30	2.1	1.6	1.5	-1.9	1.8	1.1
35	2.4	1.7	1.8	-2.2	1.9	1.0
40	2.7	1.7	2.1	-2.5	1.9	1.0
50	3.3	1.7	2.7	-3.1	2.0	0.9
60	3.9	1.8	3.3	-3.7	2.2	0.8
70	4.6	1.9	3.8	-4.3	2.3	0.6
80	5.2	1.9	4.4	-4.8	2.3	0.5
90	5.8	2.0	5.0	-5.4	2.3	0.4
100	6.5	2.1	5.6	-6.0	2.3	0.3

*Tangent Point Distance = 25 nm

Table 3.13 Dynamic Response Test Number III With Enroute Sensitivity

ALONGTRACK DISTANCE	TABLE 3.9*		SIMULATION			
	XTRK	ATRK	XTRK		ATRK	
			TO WAYPOINT	FROM WAYPOINT	TO WAYPOINT	FROM WAYPOINT
0	0.7	1.5	-0.2	-0.2	1.5	1.5
5	0.8	1.5	0.0	-0.5	1.5	1.4
10	1.0	1.6	0.4	-0.8	1.5	1.3
15	1.2	1.6	0.7	-1.1	1.6	1.3
20	1.5	1.6	0.9	-1.4	1.7	1.2
25	1.8	1.6	1.3	-1.6	1.8	1.1
30	2.1	1.6	1.5	-1.9	1.8	1.1
35	2.4	1.7	1.8	-2.2	1.9	1.0
40	2.7	1.7	2.1	-2.5	1.9	1.0
50	3.3	1.7	2.7	-3.1	2.0	0.9
60	3.9	1.8	3.3	-3.7	2.1	0.7
70	4.6	1.9	3.8	-4.2	2.3	0.6
80	5.2	1.9	4.4	-4.9	2.4	0.5
90	5.8	2.0	5.0	-5.4	2.6	0.4
100	6.5	2.1	5.6	-6.0	2.3	0.3

*Tangent Point Distance = 25 nm

Dynamic Response Test Number IV

During this test, shown in Figure 3.13, the aircraft remained within the route width requirements of AC-90-45A and Table 3.9 limits for crosstrack errors. However, the alongtrack errors were slightly larger by 0.1 to 0.5 nm (Table 3.14). The stepwise path shown in the plot is predominately due to the manual pilot control function at slow airspeeds (100 kts and below). What the manual pilot does is maintain a correction heading until the RNAV unit (CDI) tells the manual pilot it is off course by so much, at which time the pilot makes another heading correction.

Table 3.14 Dynamic Response Test Number IV

ALONGTRACK DISTANCE	TABLE 3.9*		SIMULATION			
	XTRK	ATRK	XTRK		ATRK	
			TO WAYPOINT	FROM WAYPOINT	TO WAYPOINT	FROM WAYPOINT
0	0.7	1.5	-0.2	-0.2	1.5	1.5
5	0.8	1.5	0.1	-0.5	1.5	1.4
10	1.0	1.6	0.4	-0.8	1.6	1.3
15	1.2	1.6	0.6	-1.1	1.7	1.3
20	1.5	1.6	0.9	-1.4	1.7	1.2
25	1.8	1.6	1.2	-1.7	1.7	1.2
30	2.1	1.6	1.5	-1.9	1.8	1.1
35	2.4	1.7	1.8	-2.2	1.9	1.0
40	2.7	1.7	2.1	-2.5	1.9	1.0
50	3.3	1.7	2.7	-3.1	2.1	0.8
60	3.9	1.8	3.3	-3.7	2.1	0.8
70	4.6	1.9	3.9	-4.3	2.3	0.6
80	5.2	1.9	4.4	-4.8	2.4	0.5
90	5.8	2.0	5.0	-5.4	2.5	0.4
100	6.5	2.1	5.6	-6.0	2.3	0.3

*Tangent Point Distance = 25 nm

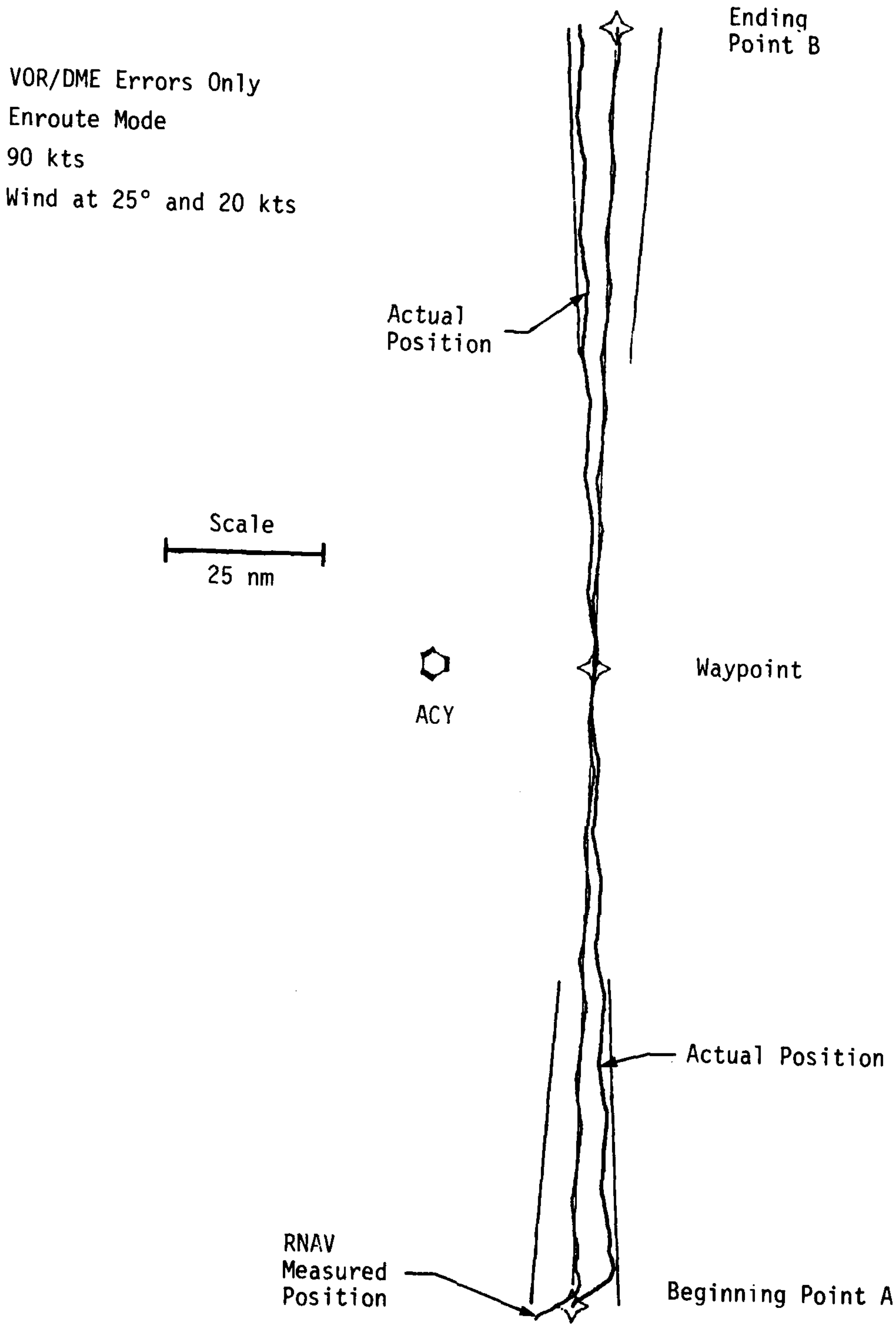


Figure 3.13 Dynamic Response Test Number IV

Dynamic Response Test Number V

As in previous tests, the crosstrack errors are within AC-90-45A (Table 3.9) requirements, but the alongtrack errors to Waypoint exceeded the requirements by 0.1 to 0.6 nm at the farther distances, as shown in Table 3.15.

The plot in Figure 3.14 shows an overshoot right of track exceeding the route width. This was due to the inability at 540 kts of the manual pilot to respond quickly enough to the RNAV crosstrack indication. This is indicative of what may occur when changing from one VORTAC to another with the possibility of encroaching on neighboring airspace.

Table 3.15 Dynamic Response Test Number V

ALONGTRACK DISTANCE	TABLE 3.9*		SIMULATION			
			XTRK		ATRK	
	XTRK	ATRK	TO WAYPOINT	FROM WAYPOINT	TO WAYPOINT	FROM WAYPOINT
0	0.7	1.5	-0.2	-0.2	1.4	1.4
5	0.8	1.5	0.1	-0.5	1.5	1.4
10	1.0	1.6	0.3	-0.7	1.5	1.4
15	1.2	1.6	0.6	-1.0	1.6	1.3
20	1.5	1.6	1.0	-1.4	1.7	1.3
25	1.8	1.6	1.3	-1.7	1.8	1.2
30	2.1	1.6	1.5	-1.9	1.8	1.1
35	2.4	1.7	1.8	-2.2	1.9	1.0
40	2.7	1.7	2.1	-2.5	1.9	1.0
50	3.3	1.7	2.6	-3.1	2.1	0.8
60	3.9	1.8	3.3	-3.7	2.2	0.7
70	4.6	1.9	3.8	-4.2	2.4	0.6
80	5.2	1.9	4.5	-4.8	2.5	0.5
90	5.8	2.0	5.0	-5.4	2.4	0.4
100	6.5	2.1	5.6	-5.9	2.3	0.3

*Tangent Point Distance = 25 nm

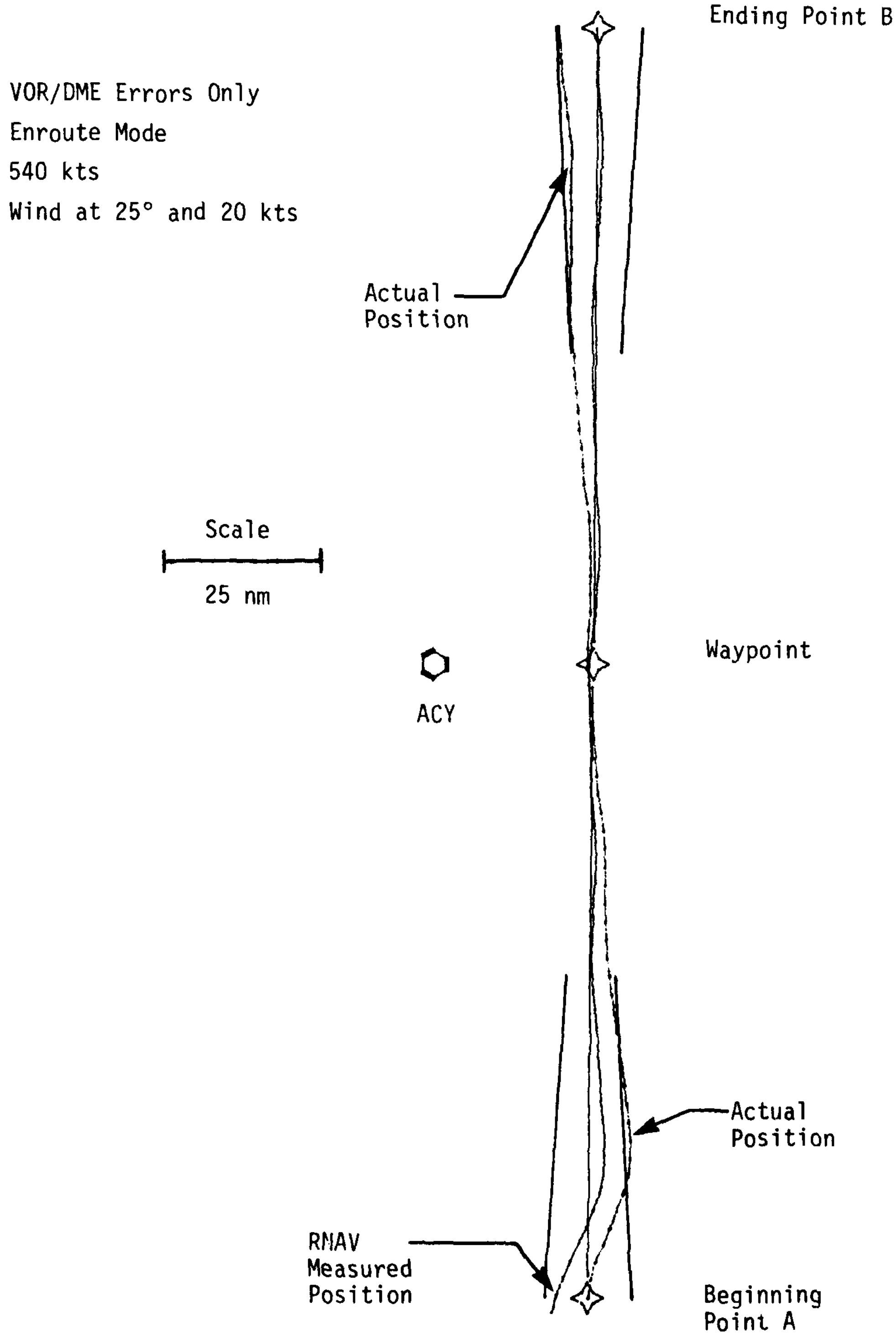


Figure 3.14 Dynamic Response Test Number V

Dynamic Response Test Number VI

Crosstrack requirements of AC-90-45A are not exceeded as shown in the plot and in Table 3.16. As in the previous tests, enroute to the tangent point waypoint, the alongtrack requirements were exceeded by 0.1 to 0.2 nm. Also the stepwise path evidenced in the plot of Figure 3.15 is due the 90 kt airspeed of the aircraft, and the heading hold correction function of the manual pilot.

Table 3.16 Dynamic Response Test Number VI

ALONGTRACK DISTANCE	TABLE 3.9*		SIMULATION			
			XTRK		ATRK	
	XTRK	ATRK	TO WAYPOINT	FROM WAYPOINT	TO WAYPOINT	FROM WAYPOINT
0	0.6	0.6	-0.2	-0.2	0.3	0.3
5	0.6	0.6	0.1	-0.5	0.5	0.1
10	0.8	0.7	0.5	-0.7	0.5	0.1
15	1.1	0.7	0.8	-0.9	0.5	0.1
20	1.4	0.7	1.1	-1.2	0.5	0.0
25	1.7	0.8	1.4	-1.5	0.6	-0.1
30	2.0	0.8	1.7	-1.8	0.7	-0.1
35	2.3	0.8	2.0	-2.1	0.7	-0.1
40	2.6	0.9	2.3	-2.4	0.8	-0.2
50	3.3	0.9	2.9	-2.9	0.7	-0.3

* Tangent Point Distance = 5nm

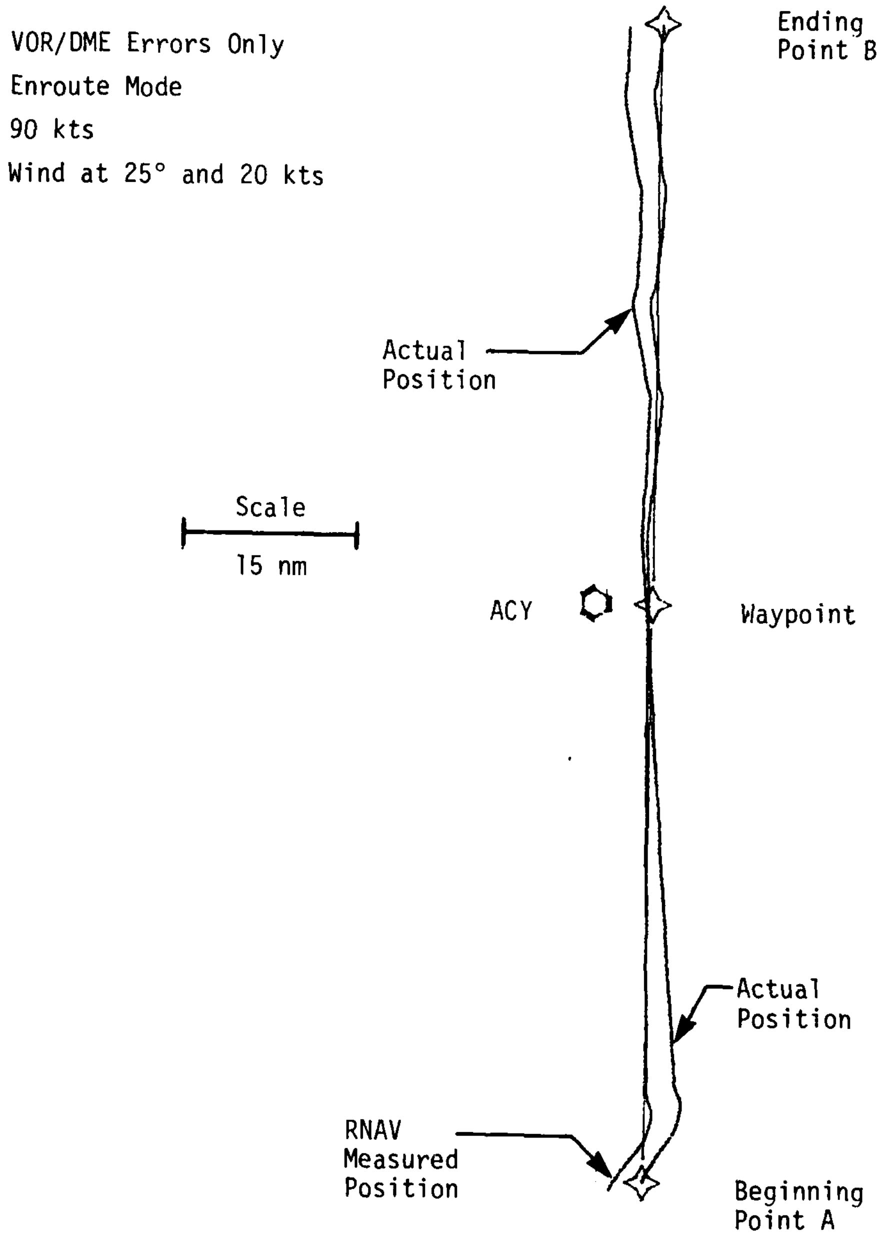


Figure 3.15 Dynamic Response Test Number VI

AD-A114 271 SYSTEMS CONTROL TECHNOLOGY INC WEST PALM BEACH FL F/G 1/4
AVIONICS CERTIFICATION REQUIREMENTS AND PROCEDURES ERROR BUDGET--ETC(U)
DEC 81 R J ADAMS DTFA01-80-4-10581

UNCLASSIFIED FAA/RD-81-107 NL

2 of 2

END
DATE
FILMED
6 82
DTIC

Dynamic Response Test Number VII

During this test neither the crosstrack or alongtrack errors exceeded AC-90-45A requirements as shown in the plot (Figure 3.16) and the Table 3.17.

This test was also run with scalloping errors as shown in Figure 3.17. Due to the scalloping reflection, there was frequent crosstrack deviation and crosstrack errors were exceeded to and from the tangent point waypoint by 0.1 to 0.7 nm (Table 3.18). The 0.7 nm crosstrack error occurred at 40 nm alongtrack to Waypoint. However, the route width requirements shown in the plot were not exceeded. Alongtrack errors were not exceeded.

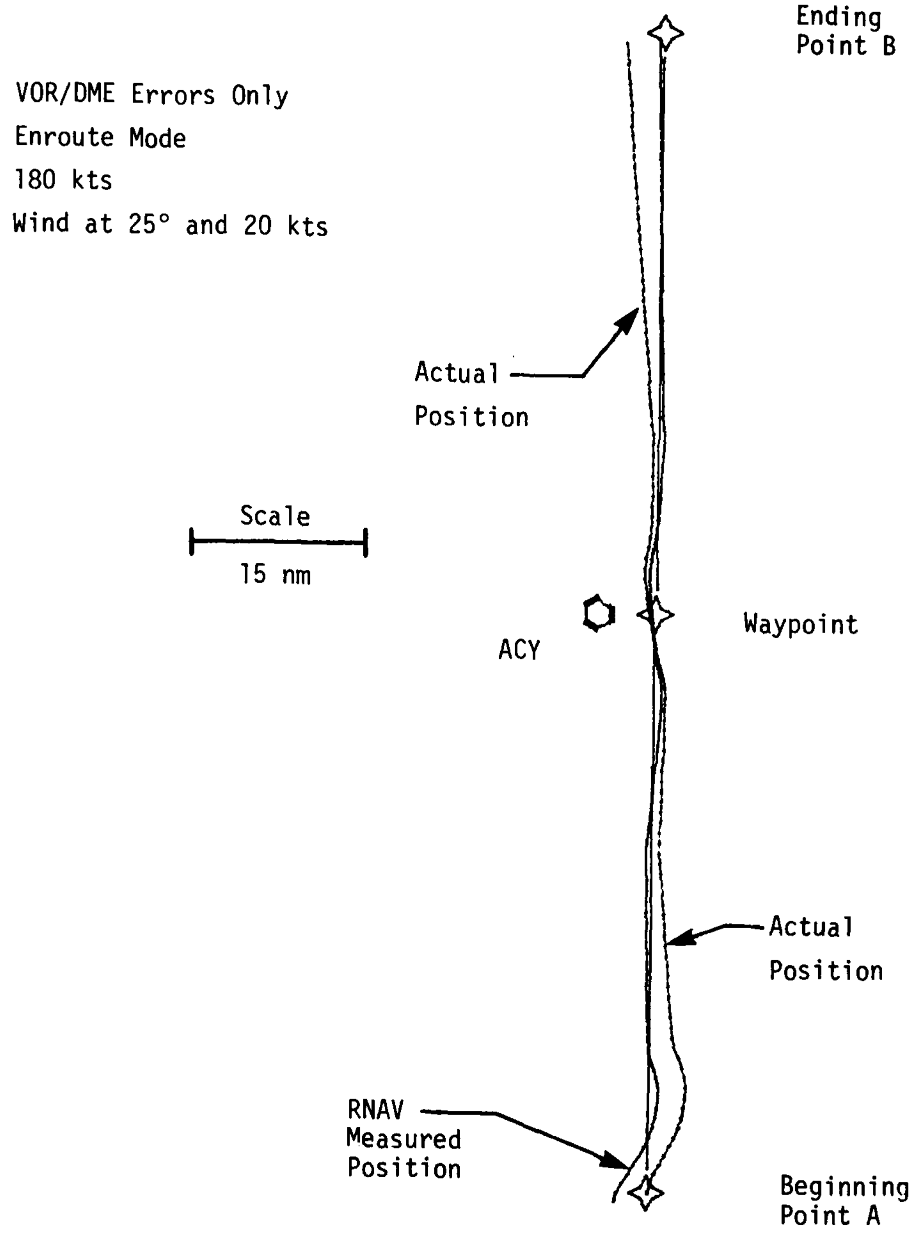


Figure 3.16 Dynamic Response Test Number VII Without Scalloping Errors

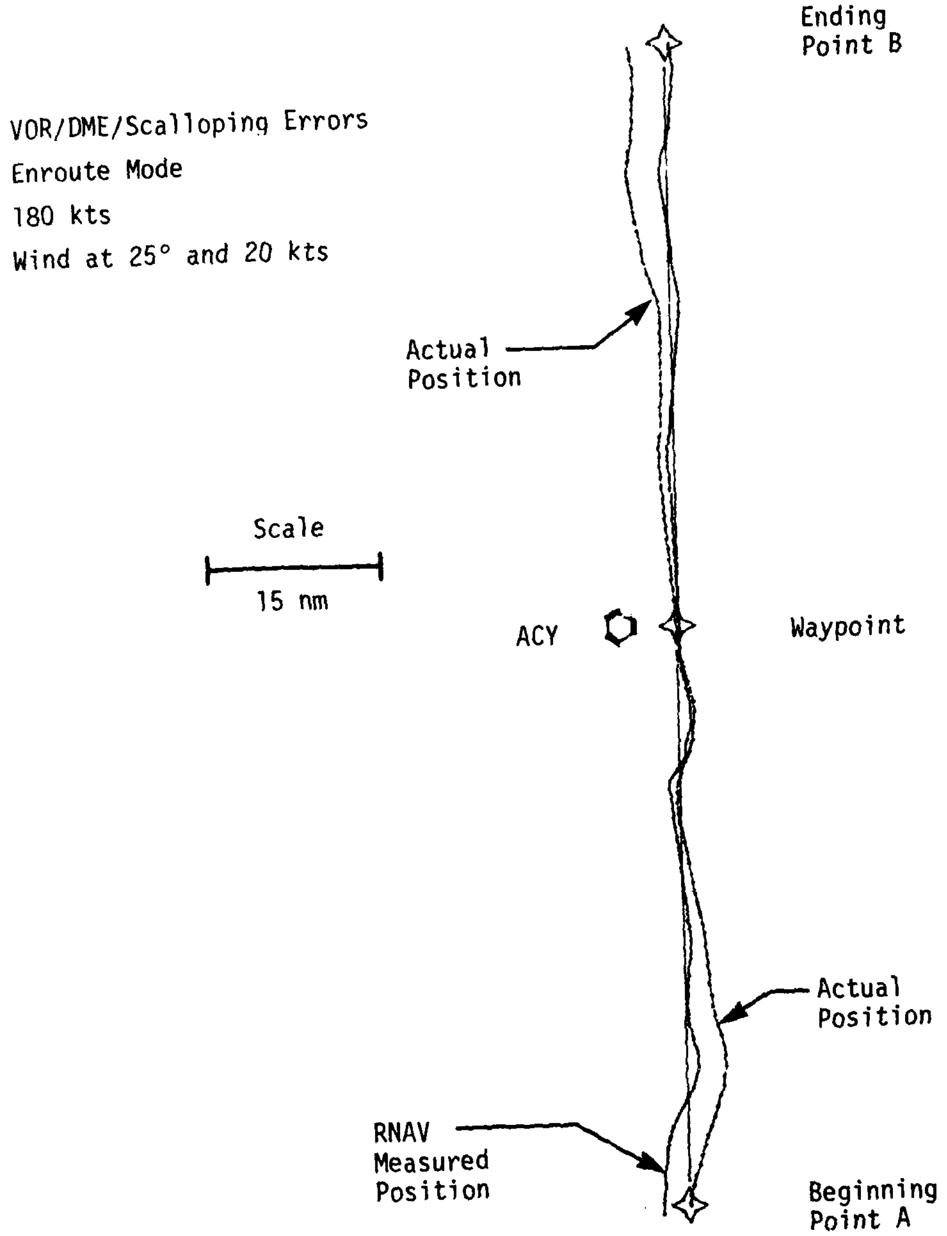


Figure 3.17 Dynamic Response Test Number VII With Scalloping Errors

Table 3.17 Dynamic Response Test Number VII Without Scalloping Errors

ALONGTRACK DISTANCE	TABLE 3.9*		SIMULATION			
	XTRK	ATRK	XTRK		ATRK	
			TO WAYPOINT	FROM WAYPOINT	TO WAYPOINT	FROM WAYPOINT
0	0.6	0.6	-0.2	-0.2	0.3	0.3
5	0.6	0.6	0.1	-0.4	0.5	0.1
10	0.8	0.7	0.5	-0.7	0.5	0.1
15	1.1	0.7	0.8	-0.9	0.5	0.1
20	1.4	0.7	1.1	-1.2	0.5	0.0
25	1.7	0.8	1.4	-1.5	0.6	-0.1
30	2.0	0.8	1.7	-1.8	0.6	-0.1
35	2.3	0.8	2.0	-2.1	0.7	-0.1
40	2.6	0.9	2.3	-2.4	0.8	-0.2
50	3.3	0.9	2.9	-2.9	0.7	-0.3

* Tangent Point Distance = 5 nm

Table 3.18 Dynamic Response Test Number VII With Scalloping Errors

ALONGTRACK DISTANCE	TABLE 3.9*		SIMULATION			
	XTRK	ATRK	XTRK		ATRK	
			TO WAYPOINT	FROM WAYPOINT	TO WAYPOINT	FROM WAYPOINT
0	0.6	0.6	-0.1	-0.1	0.3	0.3
5	0.6	0.6	0.1	-0.4	0.5	0.1
10	0.8	0.7	0.5	-0.7	0.6	0.0
15	1.1	0.7	0.4	-0.7	0.4	0.0
20	1.4	0.7	0.6	-1.0	0.4	0.0
25	1.7	0.8	1.0	-1.5	0.5	0.0
30	2.0	0.8	1.7	-2.2	0.7	0.0
35	2.3	0.8	2.2	-2.7	0.8	-0.1
40	2.6	0.9	3.3	-2.9	0.9	-0.2
50	3.3	0.9	2.3	-3.5	0.7	-0.3

* Tangent Point Distance = 5 nm

Dynamic Response Test Number VIII

During this flight there were no crosstrack or alongtrack errors exceeding AC-90-45A requirements of Table 3.9. This can be seen in the plot of Figure 3.18 and in Table 3.19.

Table 3.19 Dynamic Response Test Number VIII

ALONGTRACK DISTANCE	TABLE 3.9*		SIMULATION			
			XTRK		ATRK	
	XTRK	ATRK	TO WAYPOINT	FROM WAYPOINT	TO WAYPOINT	FROM WAYPOINT
0	0.6	0.6	0.1	0.1	0.5	0.5
5	0.6	0.6	0.2	-0.4	0.5	0.1
10	0.8	0.7	0.5	-0.7	0.5	0.0
15	1.1	0.7	0.8	-0.9	0.5	0.0
20	1.4	0.7	1.2	-1.2	0.6	0.0
25	1.7	0.8	1.4	-1.4	0.6	0.0
30	2.0	0.8	1.7	-1.7	0.7	-0.1
35	2.3	0.8	2.0	-2.0	0.7	-0.1
40	2.6	0.9	2.3	-2.4	0.7	-0.2
50	3.3	0.9	2.9	-2.8	0.7	-0.3

* Tangent Point Distance = 5 nm

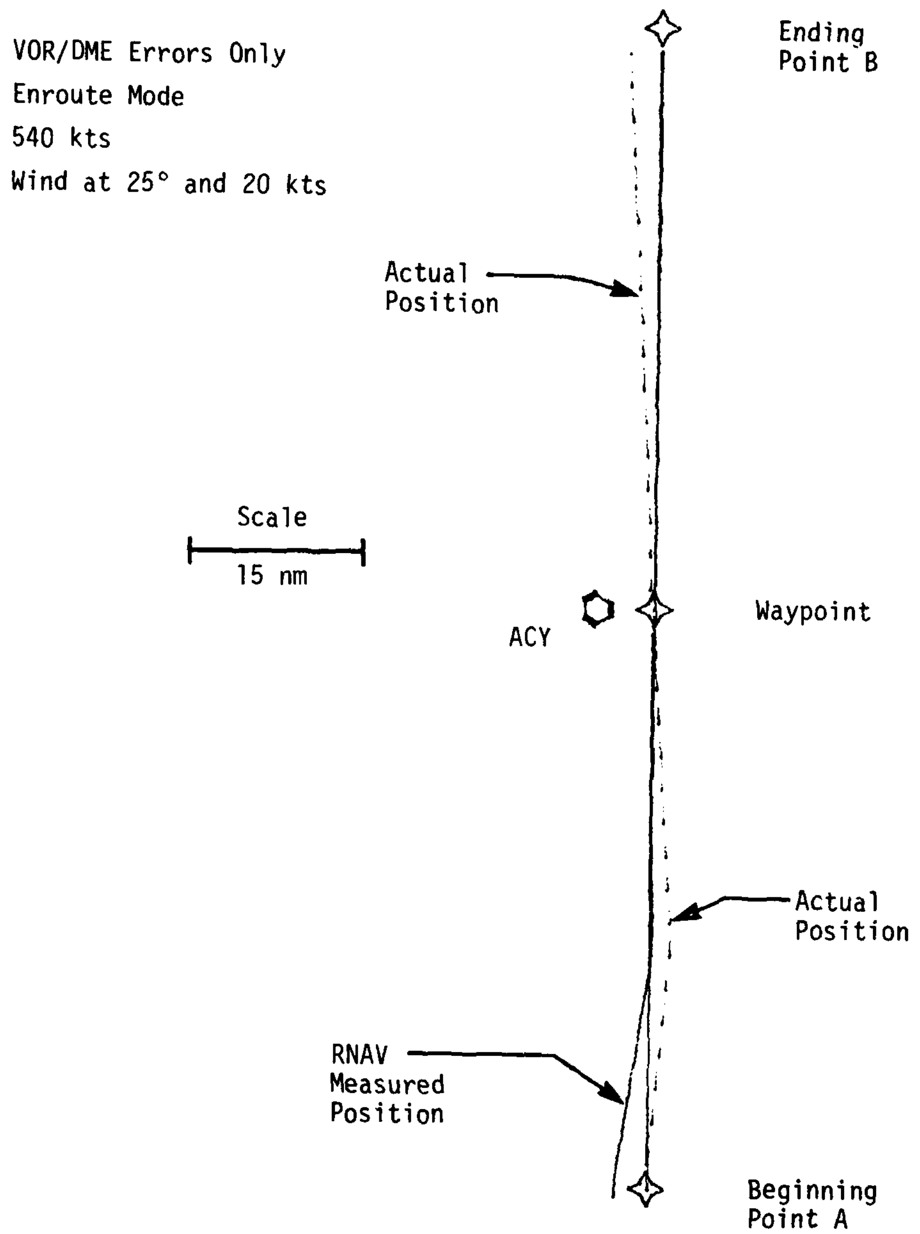


Figure 3.18 Dynamic Response Test Number VIII

Dynamic Response Test Number IX

This test was flown with approach sensitivity at 90 kts (typical helicopter or light single engine aircraft). Crosstrack errors remained within the limits of AC-90-45A, however, the alongtrack error on the leg to the tangent waypoint exceeded limits by 0.1 nm. The results are shown in Table 3.20 and Figure 3.19.

Table 3.20 Dynamic Response Test Number IX

Alongtrack Distance	Table 3.9*		Simulation			
	XTRK	ATRK	XTRK		ATRK	
			To Waypoint	From Waypoint	To Waypoint	From Waypoint
0	0.7	1.5	-0.2	-0.2	1.4	1.4
5	1.5	1.5	0.1	-0.5	1.5	1.4
10	1.0	1.6	0.4	-0.8	1.6	1.3
15	1.2	1.6	0.6	-1.1	1.6	1.3
20	1.5	1.6	0.9	-1.4	1.7	1.2
25	1.8	1.6	1.2	-1.7	1.7	1.1

*Tangent Point Distance = 25 nm

VOR/DME Errors Only
Approach Mode
90 kts
Wind at 25° and 20 kts

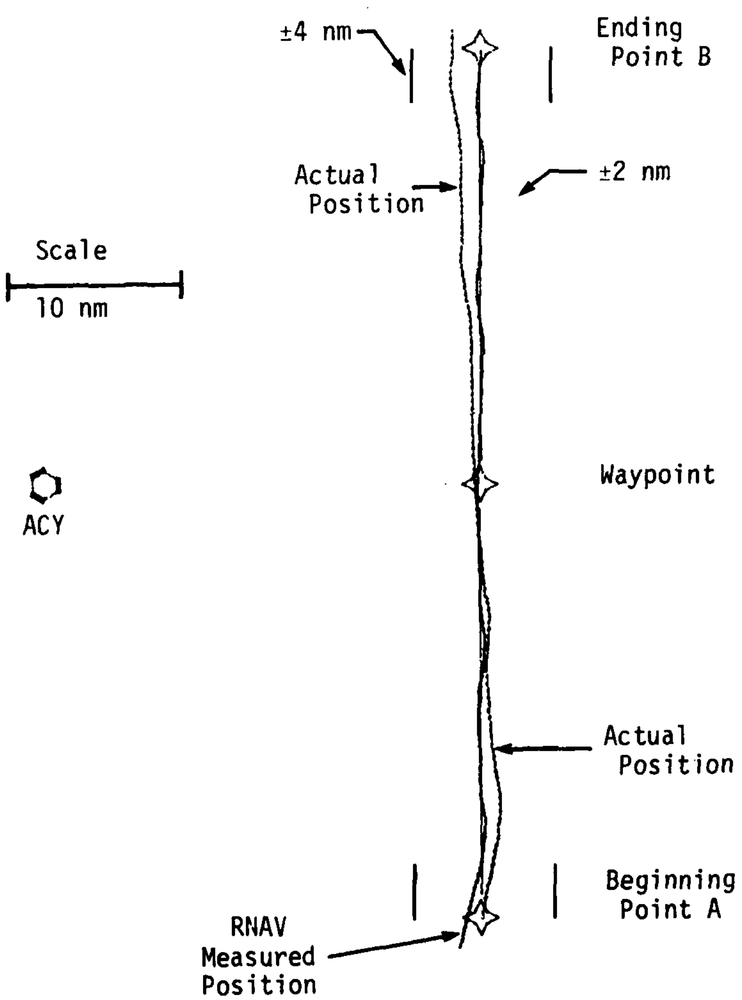


Figure 3.19 Dynamic Response Test Number IX

Dynamic Response Test Number X

This test was also flown with approach sensitivity but at 180 kts, representative of business and commercial jet aircraft. The crosstrack requirements were meet, but the alongtrack errors exceeded limits on the route to the tangent waypoint by 0.1 nm. The results are shown in Table 3.21 and Figure 3.20.

Table 3.21 Dynamic Response Test Number X

Alongtrack Distance	Table 3.9*		Simulation			
	XTRK	ATRK	XTRK		ATRK	
			To Waypoint	From Waypoint	To Waypoint	From Waypoint
0	0.7	1.5	-0.2	-0.2	1.4	1.4
5	1.5	1.5	0.1	-0.5	1.5	1.4
10	1.0	1.6	0.4	-0.8	1.6	1.3
15	1.2	1.6	0.7	-1.1	1.7	1.3
20	1.5	1.6	1.0	-1.4	1.7	1.2
25	1.8	1.6	1.2	-1.7	1.7	1.1

*Tangent Point Distance = 25 nm

VOR/DME Errors Only
Approach Mode
180 kts
Wind at 25° and 20 kts

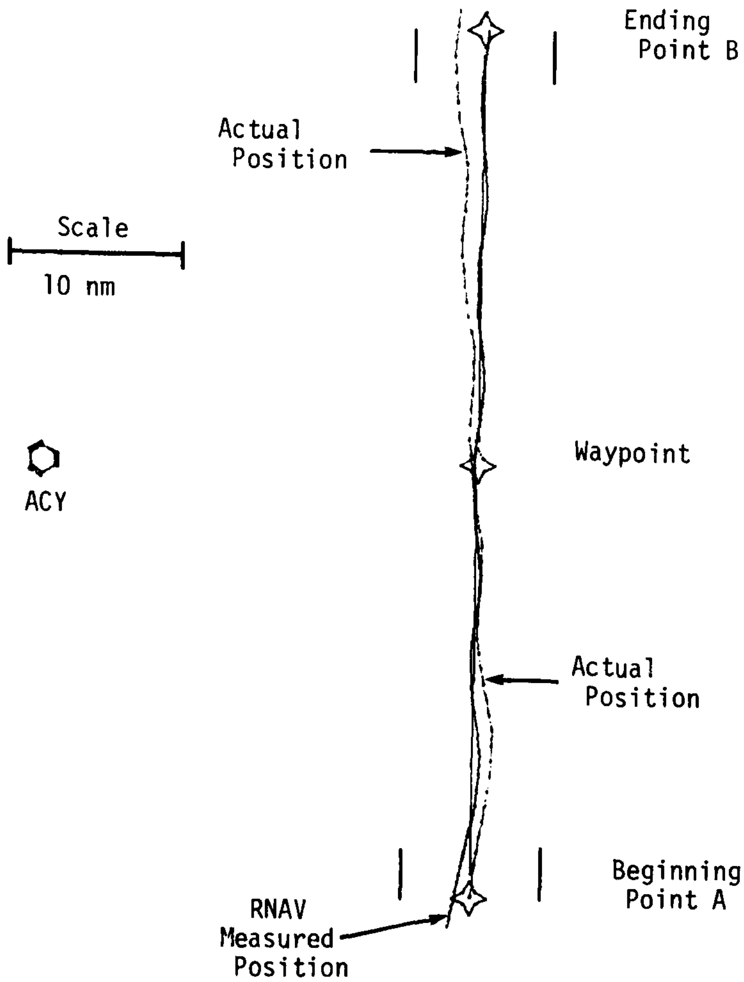


Figure 3.20 Dynamic Response Test Number X

Turn Anticipation Test Number I

This turn anticipation test was flown in the approach sensitivity mode at 180 kts. As seen in the plot of Figure 3.21 and Table 3.22, the turn anticipation, crosstrack and alongtrack error requirements were within AC-90-45A limits. The "corner cut" envelope requirement was also met.

This test was flown with scalloping errors also, resulting in consistently larger and more frequent crosstrack errors. Both crosstrack and alongtrack errors for the segment from B to D exceeded the AC-90-45A as seen in Table 3.23, although the aircraft stayed within the route width boundaries as shown in Figure 3.22.

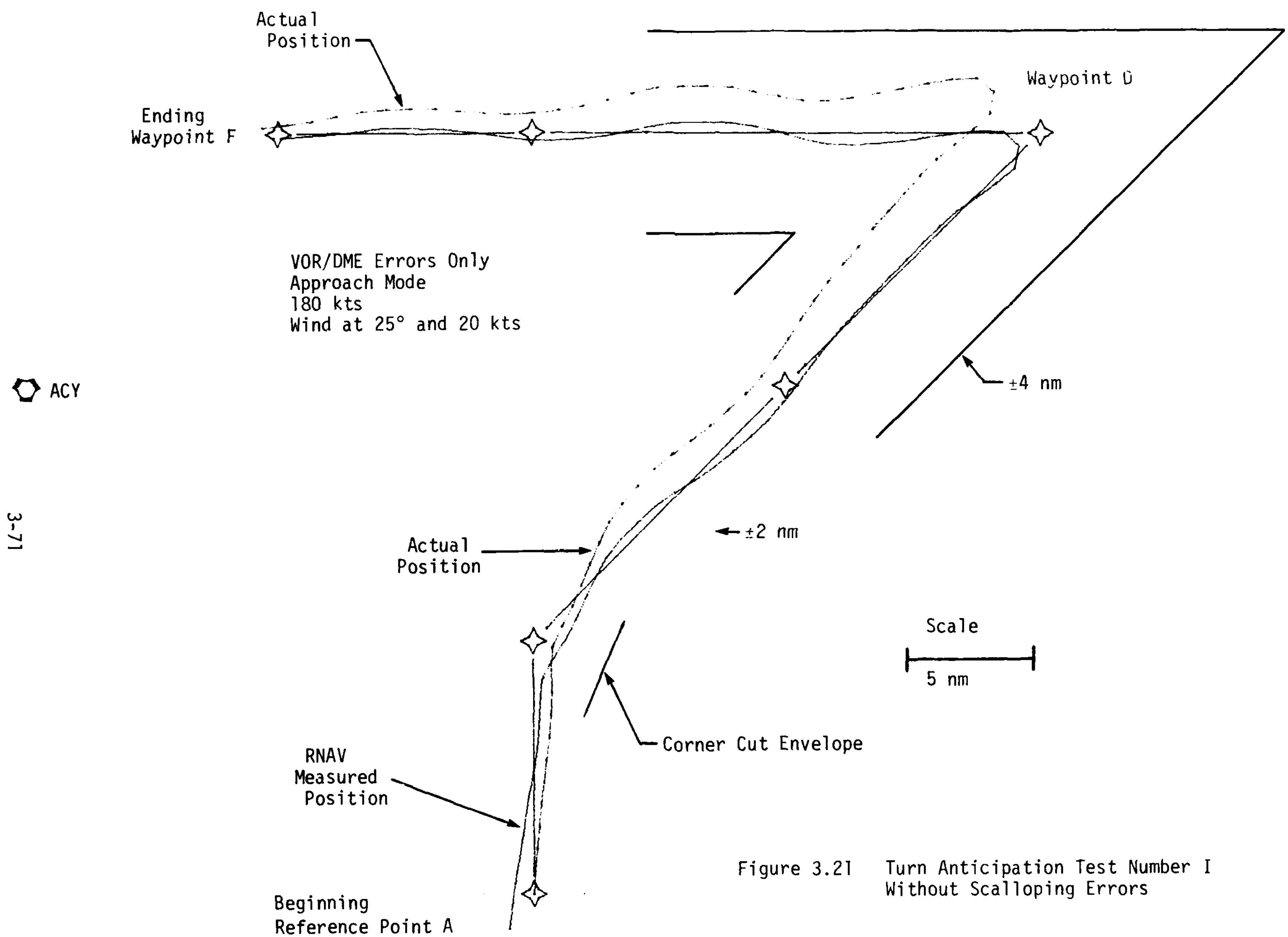


Figure 3.21 Turn Anticipation Test Number I Without Scalloping Errors

Table 3.22 Turn Anticipation Test Number I Without Scalloping Errors

Alongtrack Distance*	Table 3.9†		Simulation			
	XTRK	ATRK	XTRK		ATRK	
			A-B	B-D	A-B	B-D
0	0.6	1.3	—	—	—	—
5	0.7	1.3	—	—	—	—
10	0.9	1.3	0.5	-0.8	1.3	1.1
15	1.2	1.3	0.7	-1.1	1.3	1.0
20	1.4	1.3	1.0	-1.3	1.4	1.0
25	1.7	1.4	—	-1.7	—	0.9
30	2.0	1.4	—	-1.9	—	0.8
	Table 3.9††			D-F		D-F
0	0.6	0.8		—		—
5	0.7	0.8		—		—
10	0.9	0.8		0.5		0.7
15	1.1	0.8		0.8		0.8
20	1.4	0.9		1.1		0.8
25	1.7	0.9		1.3		0.9
30	2.0	0.9		1.6		1.0
35	2.3	1.0		1.9		1.0

*All distances are relative to the tangent point equal to zero alongtrack.
†Tangent Point Distance = 20 nm
††Tangent Point Distance = 10 nm

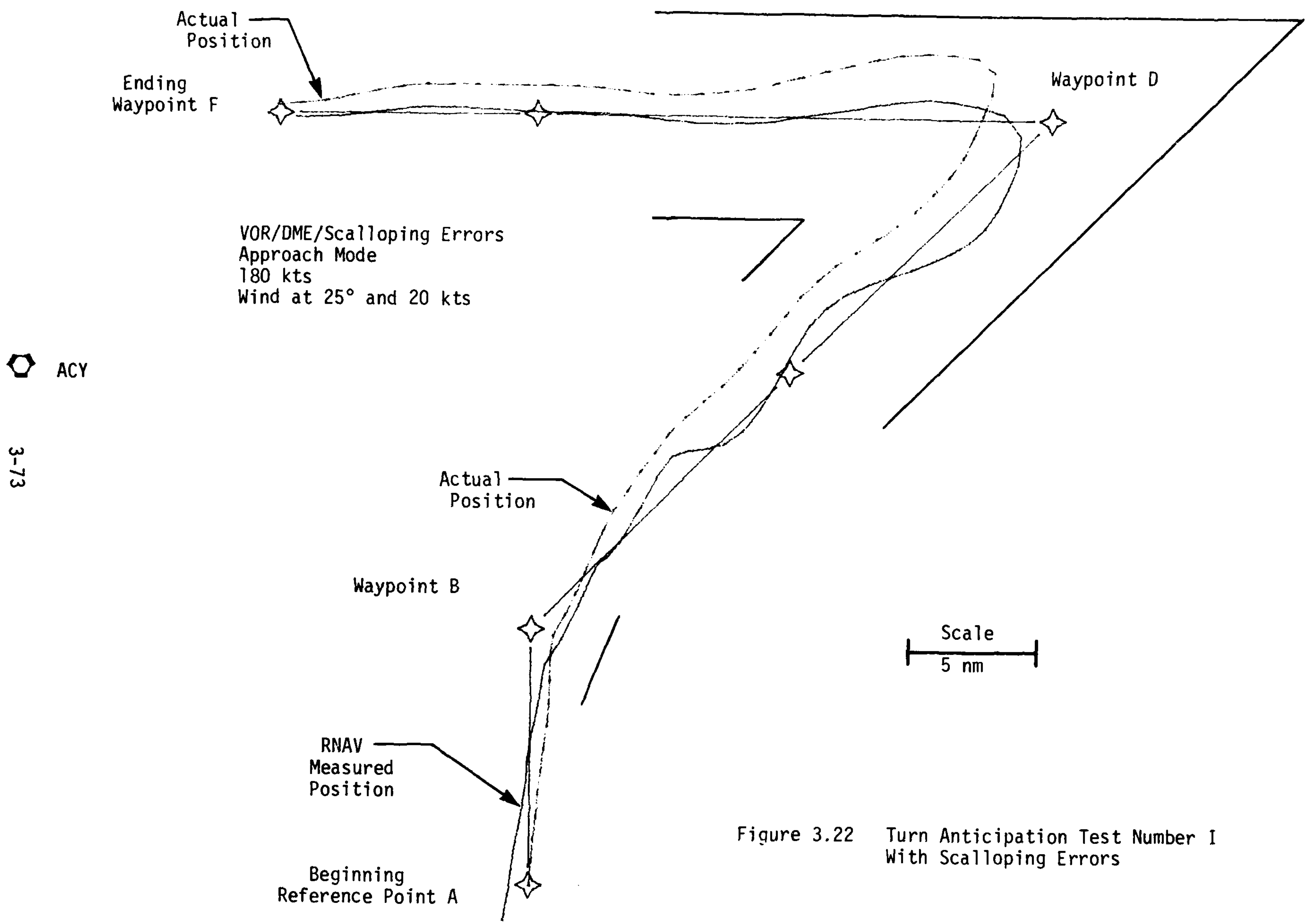


Figure 3.22 Turn Anticipation Test Number I With Scalloping Errors

Table 3.23 Turn Anticipation Test Number I With Scalloping Errors

Alongtrack Distance*	Table 3.9†		Simulation			
	XTRK	ATRK	XTRK		ATRK	
			A-B	B-D	A-B	B-D
0	0.6	1.3	—	—	—	—
5	0.7	1.3	—	—	—	—
10	0.9	1.3	0.3	-0.7	1.1	1.0
15	1.2	1.3	0.6	-0.7	1.3	0.5
20	1.4	1.3	1.0	-1.8	1.4	1.5
25	1.7	1.4	—	-1.1	—	0.4
30	2.0	1.4	—	-2.1	—	1.0
	Table 3.1††			D-F		D-F
0	0.6	0.8		—		—
5	0.7	0.8		—		—
10	0.9	0.8		0.4		0.7
15	1.1	0.8		0.8		0.8
20	1.4	0.9		1.0		0.8
25	1.7	0.9		1.1		0.7
30	2.0	0.9		1.4		0.9
35	2.3	1.0		1.8		1.0

*Alongtrack distances are relative to the tangent point equal to zero alongtrack.

†Tangent Point Distance = 20 nm

††Tangent Point Distance = 10 nm

Turn Anticipation Test Number II

During this test shown in Figure 3.23, turn anticipation was demonstrated at 540 kts. Crosstrack errors were met within the limits of the "corner cut" envelope described in Figure 3.8. In addition, crosstrack and alongtrack errors did not exceed AC-90-45A requirements as shown in Table 3.24.

This flight was also tested with scalloping errors with the results shown in Figure 3.24 and Table 3.25. Although the path was not as smooth as the previous plot, the turn anticipation limits were met. On segment B to D crosstrack and alongtrack requirements were exceeded by 0.1 to 0.4 nm and 0.1 to 0.2 nm, respectively. The only point of question is the crosstrack error of 2.6 nm that occurred at 35 nm from the tangent point distance on leg D-F, which did not meet the requirement of 2.3 nm. This error occurred during a turn and was well within turn anticipation requirements by at least two nm.

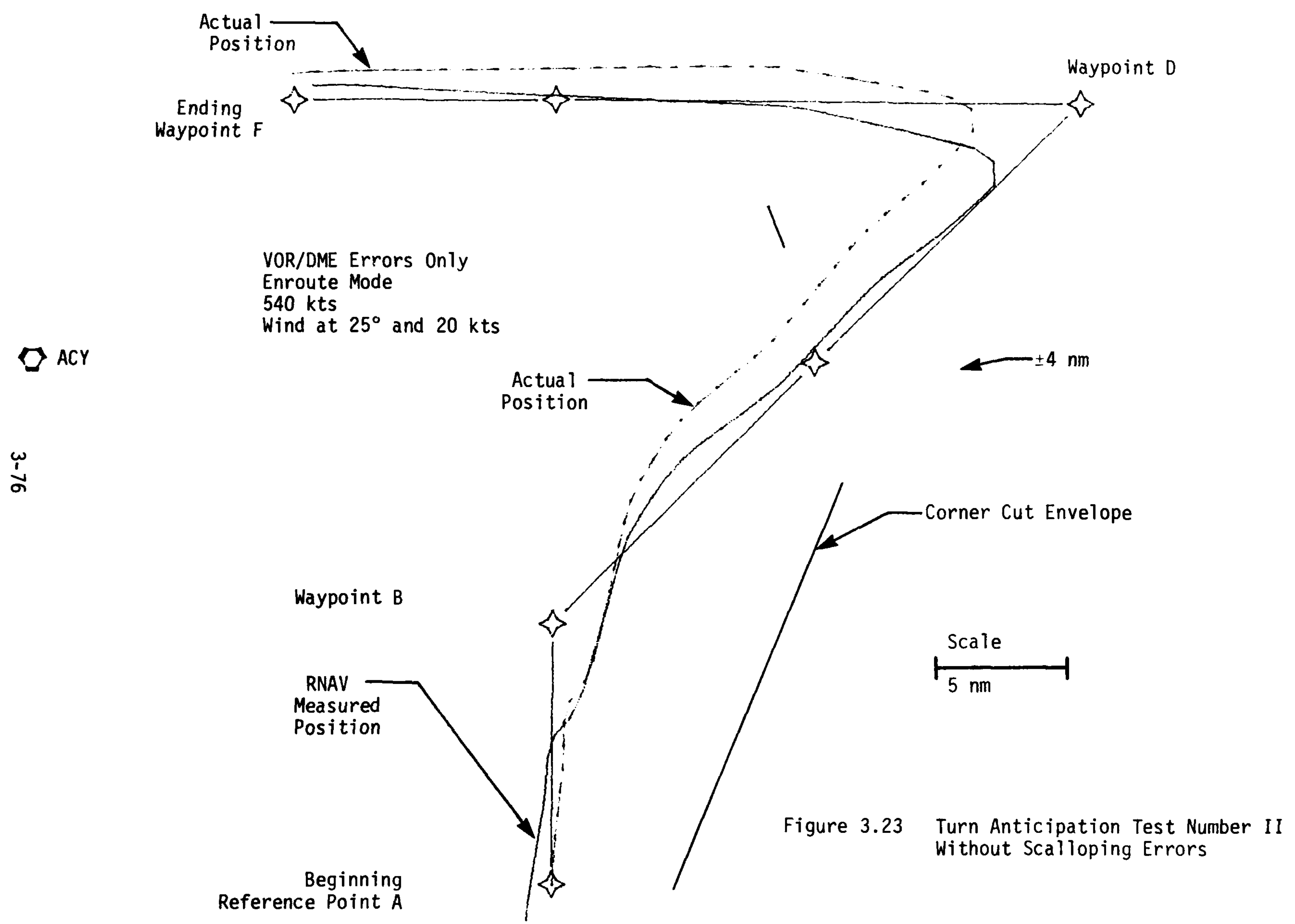


Figure 3.23 Turn Anticipation Test Number II Without Scalloping Errors

Table 3.24 Turn Anticipation Test Number II Without Scalloping Errors

Alongtrack Distance*	Table 3.9		Simulation			
	XTRK	ATRK	XTRK		ATRK	
			A-B	B-D	A-B	B-D
0	0.6	1.3	—	—	—	—
5	0.7	1.3	—	—	—	—
10	0.9	1.3	-0.6	-0.8	1.3	1.2
15	1.2	1.3	0.7	-1.1	1.3	1.0
20	1.4	1.3	1.0	-1.3	1.4	0.9
25	1.7	1.4	—	-1.6	—	0.9
30	2.0	1.4	—	-2.0	—	0.8
	Table 3.9††			D-F		D-F
0	0.6	0.8		—		—
5	0.7	0.8		—		—
10	0.9	0.8		0.4		0.8
15	1.1	0.8		0.8		0.8
20	1.4	0.9		1.0		0.8
25	1.7	0.9		1.3		0.9
30	2.0	0.9		1.7		0.9
35	2.3	1.0		2.0		0.9

*Alongtrack distances are relative to the tangent point equal to xero alongtrack.
†Tangent Point Distance = 20 nm
††Tangent Point Distance = 10 nm

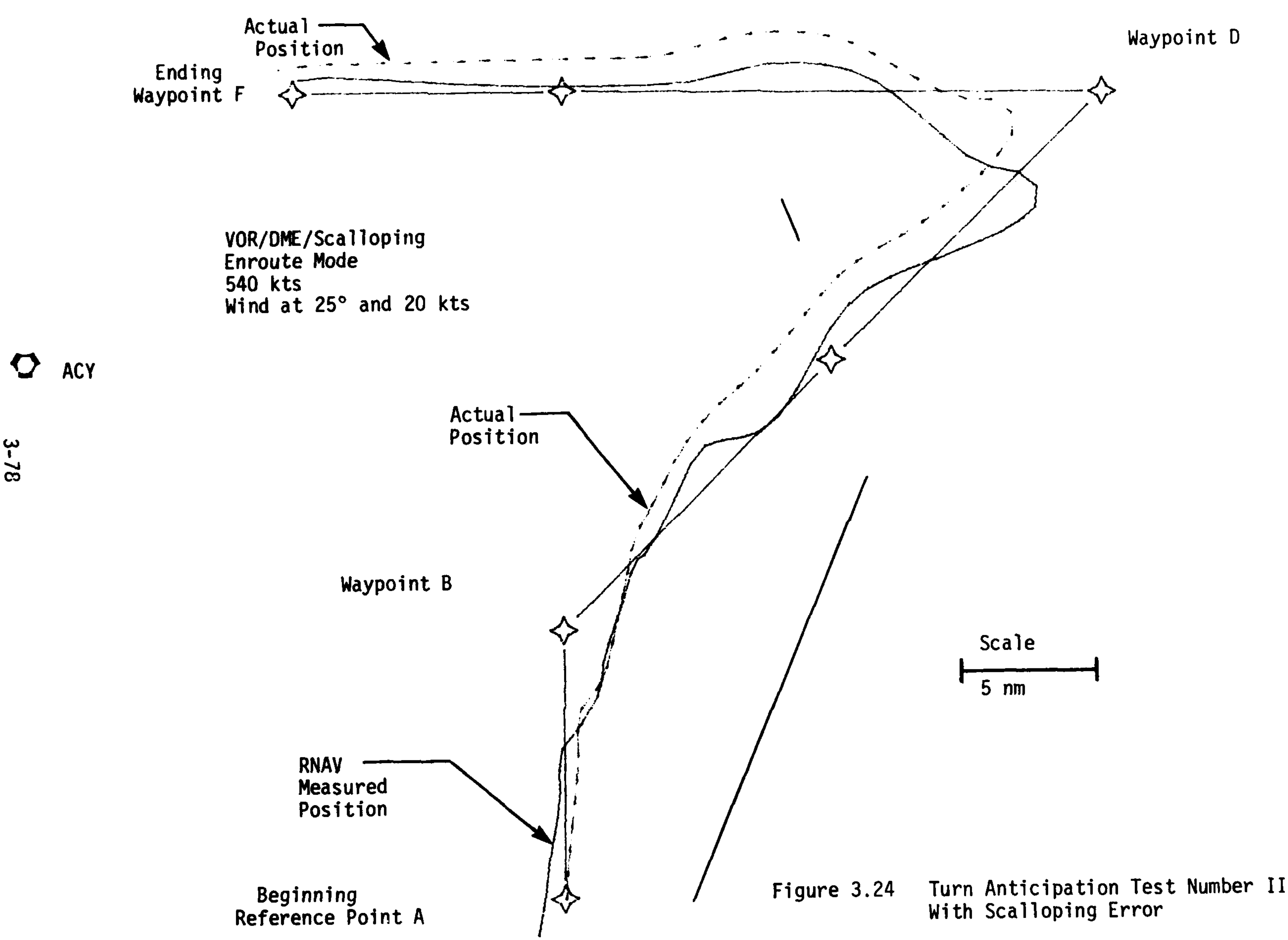


Figure 3.24 Turn Anticipation Test Number II With Scalloping Error

Table 3.25 Turn Anticipation Test Number II With Scalloping Errors

Alongtrack Distance*	Table 3.9†		Simulation			
	XTRK	ATRK	XTRK		ATRK	
			A-B	B-D	A-B	B-D
0	0.6	1.3	—	—	—	—
5	0.7	1.3	—	—	—	—
10	0.9	1.3	-0.6	-0.7	1.3	1.0
15	1.2	1.3	0.6	-0.7	1.3	0.5
20	1.4	1.3	1.0	-1.8	1.4	1.5
25	1.7	1.4	—	-1.1	—	0.4
30	2.0	1.4	—	-2.1	—	1.0
	Table 3.9††			D-F		D-F
0	0.6	0.8		—		—
5	0.7	0.8		—		—
10	0.9	0.8		0.5		0.8
15	1.1	0.8		0.8		0.8
20	1.4	0.9		1.0		0.8
25	1.7	0.9		1.1		0.8
30	2.0	0.9		1.3		0.9
35	2.3	1.0		2.6		1.0

*Distances are relative to the tangent point equal to zero alongtrack.
†Tangent Point Distance = 20 nm
††Tangent Point Distance - 10 nm

Waypoint Change Response Test

This test was run once with VOR bias and DME errors and once with VOR/DME and scalloping errors.

The run with sensor errors did not exceed AC-90-45A route width errors during the leg change transition. As shown in the plot, Figure 3.25, the RNAV unit made the leg change transition with near center line accuracy.

The second run with sensor and scalloping errors typifies a more real world case. Although this flight satisfied the route width requirements, as shown in Figure 3.26, it did exceed both the crosstrack and alongtrack during the first six nm after changing legs, as shown in Table 3.26.

The requirement for passing this test was for the RNAV unit to produce a centered crosstrack indication within the limits of Table 3.9 and within five seconds after. For the first five seconds after the turn the crosstrack and along track errors were -0.65 nm and 2.61 nm, respectively. These are within Table 3.9 limits of 1.0 and 3.5 nm crosstrack and alongtrack, respectively.

As for a centered crosstrack indication, the RNAV measured position during the first five seconds ranged between -0.3 and -0.5 nm or about ½ dot right CDI deflection in the enroute mode. This is shown in Table 3.27.

Table 3.26 Waypoint or Leg Sequencing Accuracy Test With Scalloping Errors

Alongtrack Distance†	Table 3.9††		Simulation	
	XTRK	ATRK	XTRK	ATRK
0	1.0	3.5	-0.6	2.6
1*	1.0	3.5	-0.7	2.7
2*	1.0	3.5	-0.8	3.9
3*	1.0	3.5	-1.0	4.6
4*	1.0	3.5	-1.0	4.5
5	1.0	3.5	-1.1	4.2
6*	1.0	3.5	-1.1	3.9

*Intermediate points were interpolated from Table 3.9.
†Distances are relative to the tangent point equal to zero alongtrack.
††Tangent Point Distance = 60 nm.

Table 3.27 Waypoint or Leg Sequencing Response Time Test With Scalloping Errors

Seconds Enroute to WP 2	RNAV Measure Crosstrack Error
0	-.5
1	-.4
2	-.4
3	-.4
4	-.3
5	-.3

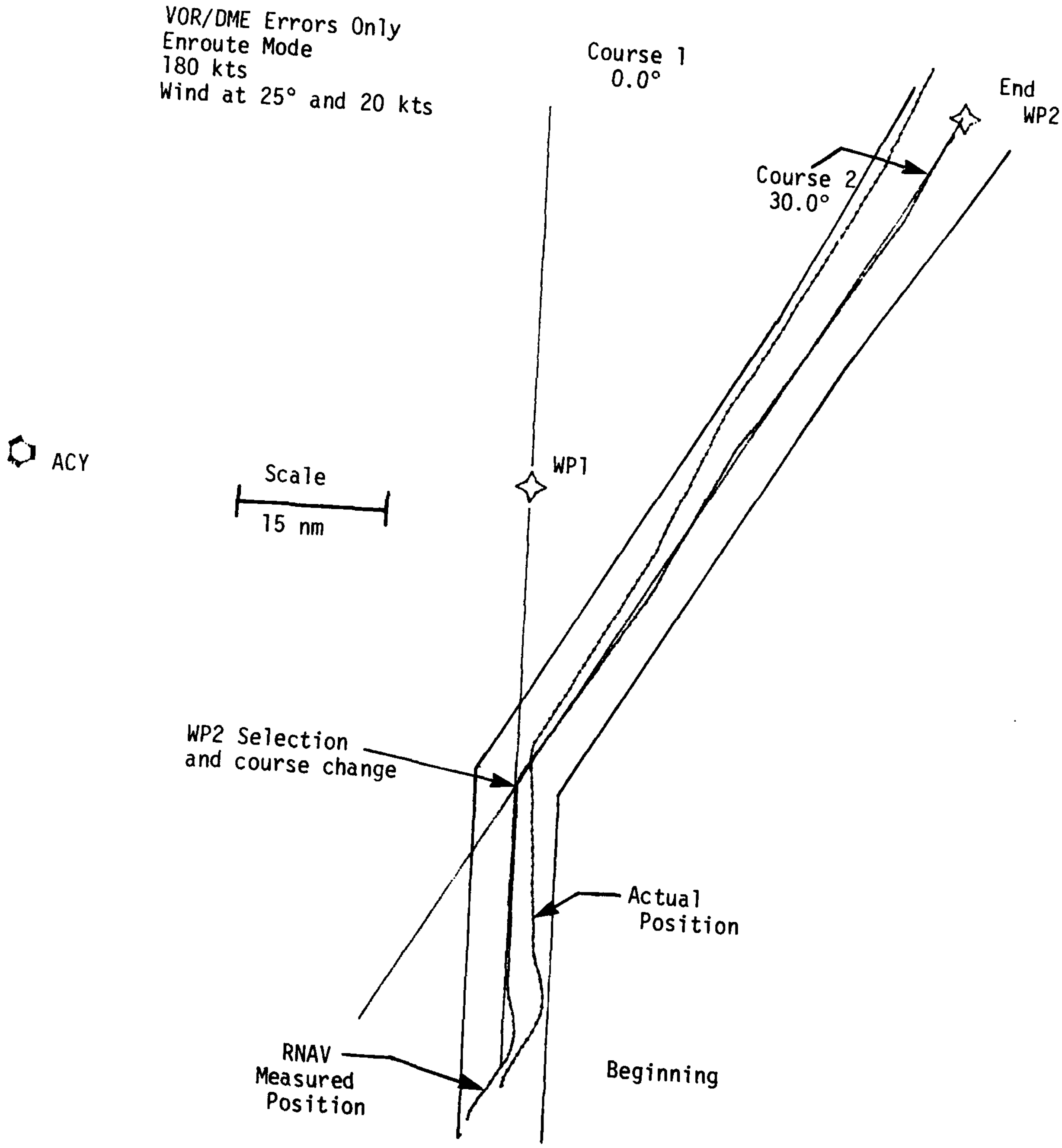


Figure 3.25 Waypoint or Leg Sequencing Without Scalloping Errors

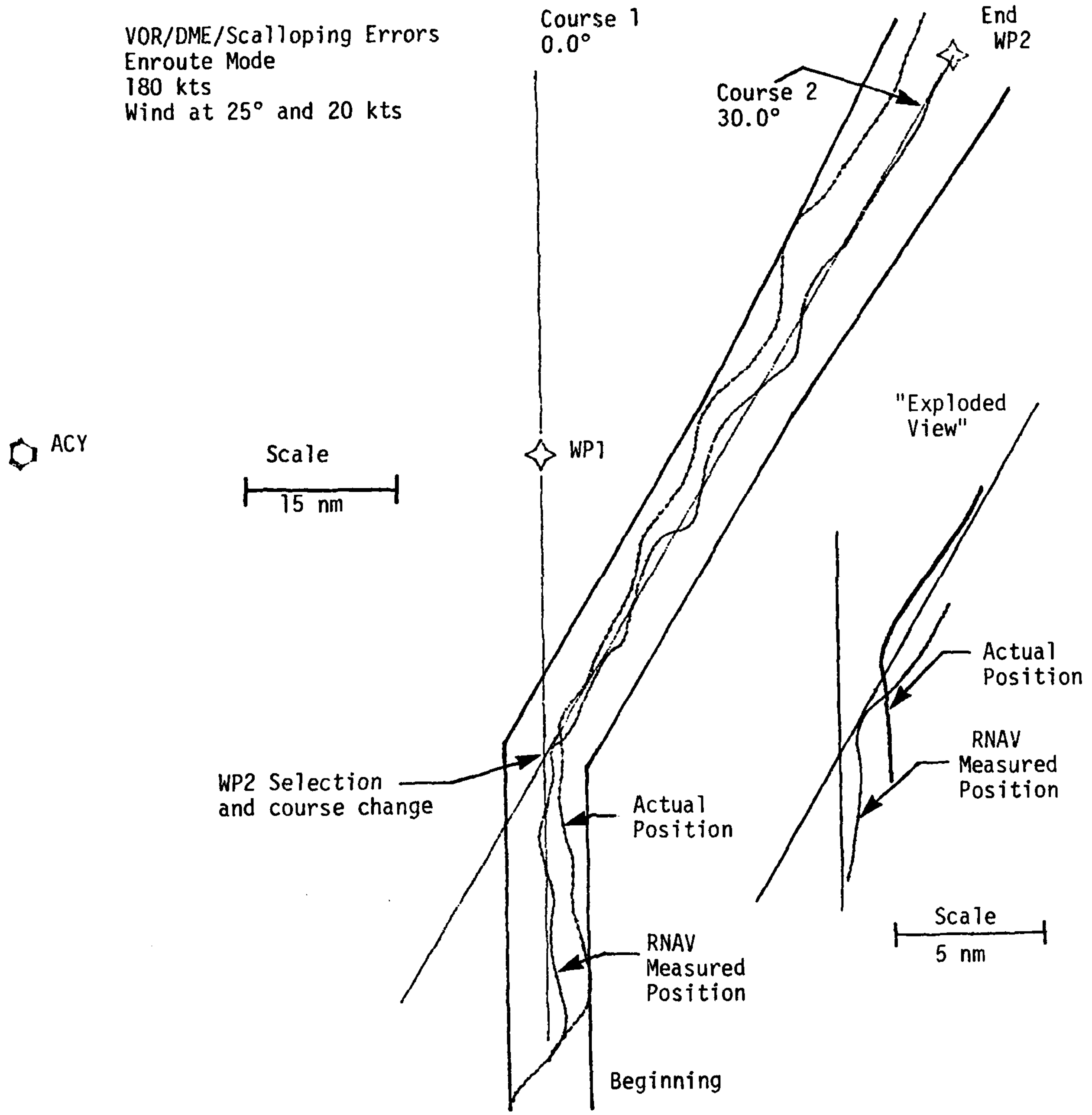


Figure 3.26 Waypoint or Leg Sequencing With Scalloping Errors

Direct-To Function Test

The purpose of this test was to illustrate that the RNAV unit would not "S" turn during transition to intercept the direct-to waypoint leg.

The direct-to waypoint was defined as waypoint F, and the leg change waypoint as 14.2 nm to waypoint D, the distance from reference point C to waypoint D. When the RNAV unit measures 14.2 nm to go to waypoint D, the unit creates the leg change waypoint ahead of the measured distance by an amount equal to the turn anticipation (in the case 2.0 nm). Therefore, the RNAV unit intercepts the new course to the direct-to waypoint at 12.2 nm to waypoint D. The new course is shown in Figure 3.27 as the short dashed line. The alternating dashed line represents the supposed or intended course.

As shown in Figure 3.27, the RNAV unit provided guidance to the leg so as not to "S" turn during the transition to intercept. It should also be noted that the route width requirements for such a direct-to leg must accommodate any turn anticipation used.

There were no accuracy requirements associated with the test definition. However, establishing accuracy requirements should be given consideration in light of the previous demonstration.

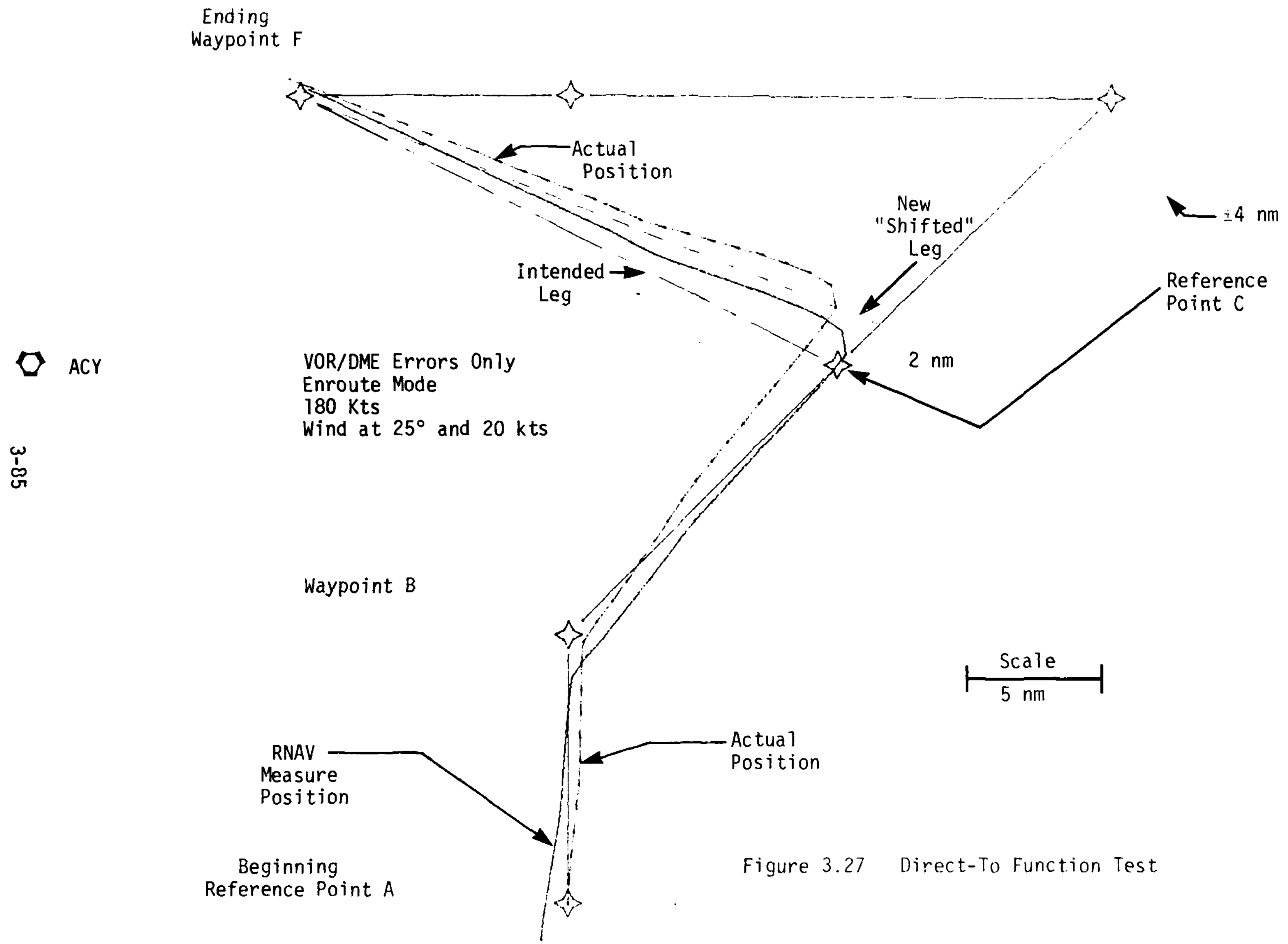


Figure 3.27 Direct-To Function Test

3.4.3 Dynamic Test Conclusions

Performance of the Dynamic Tests by the SCT fast time RNAV modeled aircraft simulator revealed some interesting aspects, affecting error budget analysis, worth further consideration and analysis.

- The Dynamic Response Test demonstrated that the RNAV equipment could be adequately analyzed for providing guidance to meet AC-90-45A crosstrack and alongtrack error requirements. However, it was also shown in Test III and V that the Dynamic Response Test should also include system dynamics of RNAV equipment in the selection and change from one active Vortac to another while on the same course. Congruently, error budgeting should also be considered to accommodate the associated shift in track for both enroute and terminal area (multiple leg) operations.

- It was demonstrated for most tests the importance of scalloping errors in providing near real world error source simulation. It has also been pointed out that only one scalloping reflector is not sufficient to demonstrate the common RNAV guidance errors associated with combined (VOR/DME/Scalloping Reflector) sensor errors.

  The recommended alternative mentioned in Section 3.4.1, is to model the characteristics of the power spectral density associated with the combination of all sensor errors as an aircraft tranverses VORTAC radials.

- In the Direct-To-Function Test the impact of turn anticipation was demonstrated. As described earlier, when the aircraft reached the point at which it was commanded to turn to intercept the leg to the direct-to waypoint, the RNAV equipment created a new turning point. This new point was two nm past the desired or intended turning point since there was two nm of turn anticipation in the RNAV equipment. This new point shifted the intended intercept leg to the north. When this occurs, the associated airspace allowances for that leg also changes.

It should be determined whether or not RNAV manufacturers program the turn anticipation function also into the direct-to function. The Direct-To-Function Test would not be comprehensive enough without a demonstration of the system dynamics and meeting Table 3.9 and AC-90-45A airspace requirements. The associated impact on error budgeting should also be investigated.

- Although it was not demonstrated in the Dynamic Tests, the impact of flying in the autopilot mode on meeting Table 3.9 and AC-90-45A requirements needs further investigation. Manual controlled flight with RNAV is characteristic of frequent course correction heading changes. This is because the pilot is more responsive to CDI deflection. An autopilot controlled flight with RNAV is characteristic of less frequent and smaller course correction heading changes. This also varies with the airspeed of the aircraft. Therefore, larger and prolonged crosstrack errors are not uncommon, particularly in conjunction with a turn.

  In consideration of this, the system dynamics involved in autopiloting with RNAV is necessary in judging its performance relative to AC-90-45A airspace requirements.

- Performance of the Dynamic Tests with the fast time RNAV simulator has proven several advantages over actual flight tests methods. The first obvious advantage is the fast response in error analysis. Another advantage is the relative inexpense to operate a simulator over and against flight testing. A third advantage is that it is possible to manipulate many complex and interacting variables to simulate a near real world environment. And lastly, what rarely occurs in flight tests, is that there is control over the conditions of the test in its entirety.

  The disadvantage is its theoretical treatment of the real world. However this usually outweighs the disadvantages of flight test: extensive manpower and equipment requirements,

the high operating costs, limited control over test conditions, and slow response with data analysis results.

In summary the Dynamic Tests results and the aforementioned conclusions show that just comparing error budget and system accuracy statistics is not sufficient. An analysis of the system dynamics including pilot, autopilot, combined sensor scalloping errors, and specific system function response is necessary to judge system performance relative to airspace boundaries and air traffic controller procedures.

4.0 ERROR COMBINATION AND CORRELATION ANALYSIS

The primary purpose of this section is to demonstrate the conservatism inherent in the current RNAV error combination technique. This will be accomplished by comparing computed total system crosstrack (TSCT) error data for various navigation systems with the values for TSCT error measured using tracking radar. In the process of demonstrating this conservatism, the explicit quantitative relationship between FTE and total system crosstrack error will be defined. This quantitative relationship supplements the knowledge gained implicitly in Section 3.3 about TSCT errors associated with various navigation systems and FTE errors. As in Section 3.3, the bulk of the data analyzed will be VOR/DME RNAV. However, the wide area coverage navigation system data will be included in the analysis whenever it is available and applicable.

A secondary purpose of this section will be to suggest a possible change to the RSS error combination technique which will improve the accuracy with which total system errors can be calculated from a combination of measured error sources. Available data will be used and a preliminary analysis showing the effectiveness of the suggested technique will be performed. The indicated effectiveness of the technique will be demonstrated for both airline and general aviation RNAV systems.

Finally, a third purpose of this section will be to explicitly illustrate the importance of FTE in the error combination and system approval process. Once this significance is understood, the need for additional quantitative FTE data for the wide area coverage systems becomes imperative.

The Root-Sum-Square (RSS) error combination technique simply states that the square root of the sum of the squares of the RNAV error budget components may be used to represent the total system error. In equation form and related to Type (1) area navigation error budget elements, this translates into:

$$\sigma^2_{TSCT} = \sigma^2_{VOR} + \sigma^2_{DME} + \sigma^2_{RNAV} + \sigma^2_{FTE} \; (+\,\sigma^2_{CSE})^* \qquad (1)$$

*Course Selection Error term for those systems requiring course input via a card type omni-bearing selector.

However, certain theoretical assumptions must be applied to the TSCT error budget elements in order for this relationship to be valid. The RSS assumptions include:

1) Normal distributions for the error sources.
2) Linearity - sensitivity of total system error to changes in error source magnitudes is linear (i.e., a 2° VOR error impacts TSCT the same as twice a 1° VOR error).
3) Uncorrelated, independent errors.
4) 95% probability defined by two-sigma error distribution. (This is true if (1) is true).
5) Dynamics of the system are negligible.
6) Zero mean error sources.

Up to this point, none of the above assumptions have been quantifiably verified. However, the results presented in References 1-13 indicated that at least assumptions (1), (4) and (6) were valid for flight technical error. The assumption most questionable from an analytical viewpoint is number (3). The presumed independence of FTE, RNAV computer and total system errors, as well as the assumption that these errors are uncorrelated, has gone untested for VOR/DME RNAV systems since approval began and is now being applied to wide area coverage systems without being verified. Similarly, sensor errors and computer errors are not logically assumed to be uncorrelated and independent. The reason for questioning the validity of these previously accepted assumptions is that in each case stated there is an a priori relationship of one error's magnitude as a function of the input errors from other sources. For example, any actual error in the VOR, DME, Loran-C or Omega signal received is a direct input into the navigation computer. After processing the signal and possibly some form of filtering, the output is displayed to the pilot. There is obviously a direct functional relationship between the displayed position (which adds computer and display errors) and the received signal errors. In addition, the pilot's reaction to the displayed RNAV information is definitely dependent on, and probably correlated to, one or more of the other error sources - VOR, DME, OBS, computer or display. Once the functional dependency is understood, it is possible to quantify and relate the error sources in a

mathematical sense. The functional loop is closed when the pilot's reaction to the processed and displayed sensor inputs results in aircraft movement which is recorded and measured as total system error relative to a desired course. This total system error must, therefore, be calculated by taking into account the quantifiable error correlations.

In order to substantiate or negate the suspected relationships, the error correlations must be evaluated. This evaluation will begin with an overall assessment of whether correlation exists between FTE and the net result or Total System Crosstrack error. The analysis will then progress toward establishing the precise correlation for a sample set of flight test data.

4.1 FTE, TSCT ERROR AND THE RSS ERROR COMBINATION TECHNIQUE

Currently the RSS error combination is recommended in AC90-45A, Appendix C as an error combination technique suitable for system design, airspace planning and demonstration of compliance. However, current flight test results show:

1) FTE is the same order of magnitude as system crosstrack, and not one half as large.
2) The RSS technique is conservative (33%-35%), and this may no longer be acceptable in a reduced route width environment.
3) FTE correlates with other error quantities, which invalidates the RSS assumption.

Error combination using the recommended RSS technique implicitly assumes that none of the error budget component error magnitudes will be equal to or greater than the measured total system error. That is, if during a flight test experiment, measured total system error was ±2.0 nm with a zero mean and for the same data, measured FTE was ±2.0 nm then the RSS equation cannot possibly predict the correct measured TSCT if other elements are added to FTE. For example, if the combined

ground and airborne VOR error was ±1.0 nm, the combined ground and airborne DME error was ±0.1 nm and the computer error was ±0.5 nm. The RSS technique (Equation (1)) would predict:

$$\begin{aligned} \sigma_{TSCT} &= \left[(1.0)^2 + (0.1)^2 + (0.5)^2 + (2.0)^2\right]^{1/2} \\ &= [5.26]^{1/2} \\ &= 2.29 \text{ nm} \end{aligned}$$

For the hypothetical case being discussed this would be in error by about 15%. The error would be conservative since the computed TSCT would be larger than that actually measured. This example was presented to illustrate the fact that if FTE (or any of the other error budget elements) is very close in magnitude to TSCT measured, then the RSS computed TSCT cannot be used as an accurate computation technique to predict total system error. Flight test data substantiating that this case actually exists is shown in Figure 4.1.

The data summarized graphically on Figure 4.1 was presented in tabular form in Section 3.3. It is apparent from this graphical summary that regardless of the absolute accuracy, the navigation system sophistication, or the navigation mode (manual or autopilot), current flight test results indicate that TSCT and FTE are very close to the same magnitude. This fundamental conclusion can be interpreted as an indication that for the low cost, general aviation systems, if measured TSCT is ±1.5 nm, then measured FTE will be ±1.5 nm. This is due to the lack of sophisticated sensor signal filtering by the navigation system, the types and sensitivities of displayed information, and the characteristic experience level and flying techniques of the general aviation pilots using them. This conclusion is not all that surprising. However, the lower end of the data shown in Figure 4.1 is somewhat different than expected. Based on a significant sample of both manual and autopilot flights, this data shows that even with sophisticated air carrier equipment, accurate sensor signals and with the pilot taken out of the loop (autopilot coupled), if measured TSCT is ±0.3 nm the FTE is ±0.2 nm. As stated, this type of relationship between component errors

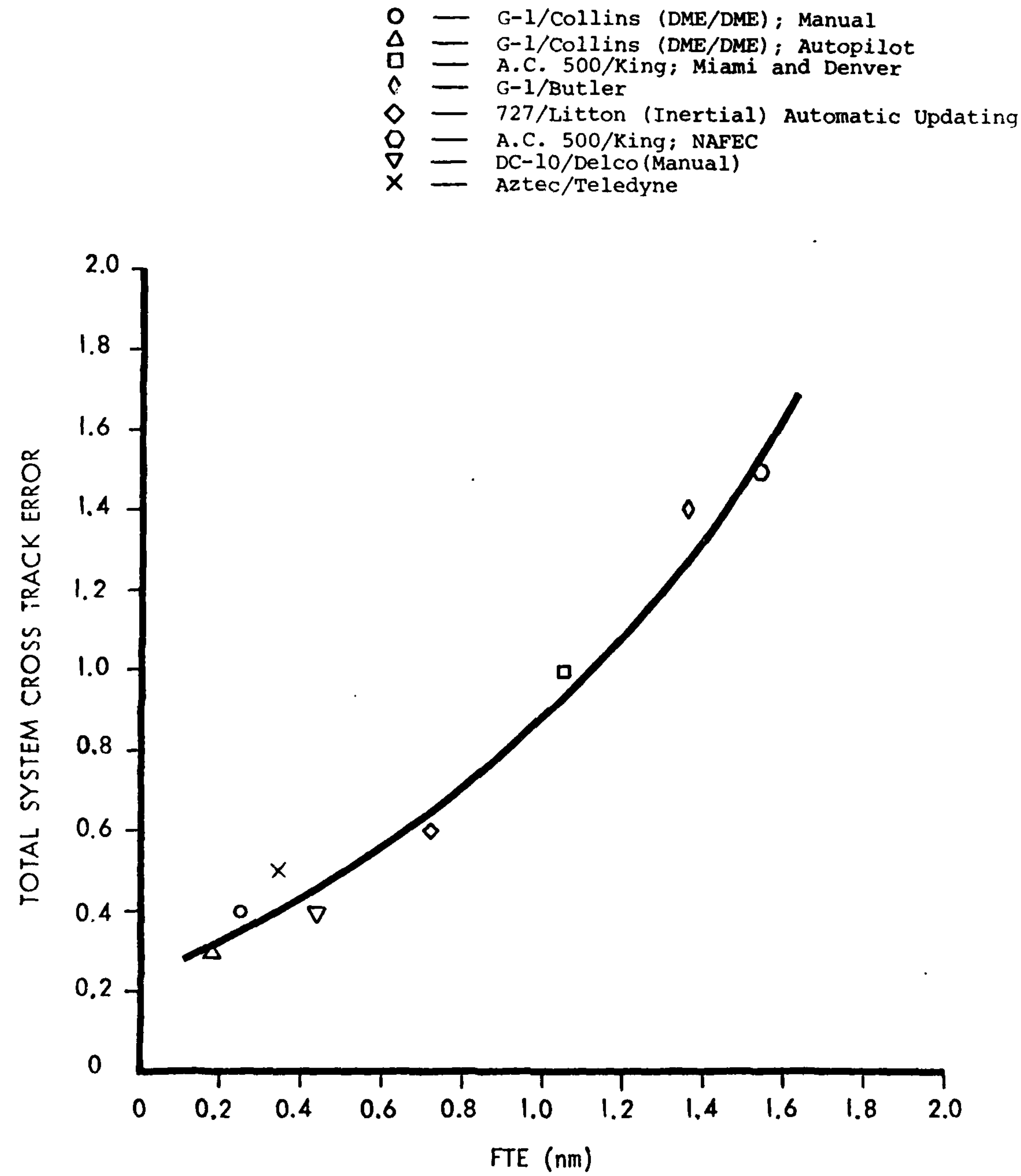


Figure 4.1 Comparison of FTE Magnitude to Total System Cross Track Error for Various Levels of RNAV Equipment (Steady State Data, Zero Mean Assumed, 2σ)

and total system error precludes use of the RSS computation technique if an accurate assessment of total system accuracy is a requirement and if tracking radar measurements of actual aircraft track are not a plausible method for obtaining the desired estimate.

Before addressing the possible alternatives to the RSS computation of TSCT error magnitudes, it is interesting to estimate the degree of conservatism resulting from the RSS method of error combination. The interest evolves from the distinct possibility that this conservatism may be a desirable element for airspace design and RNAV system certification purposes. Indeed, the standard argument that: "The RSS technique has been used successfully for years so why should it be changed now?", may be a valid point of view. The key to the validity or invalidity of this argument is whether or not a change is necessary "now" and if not now, when the change might become a requirement. Figure 4.2 can be used to explore possible answers to all of these inquiries.

The abscissa of Figure 4.2 is total system error derived from tracking radar position measurements compared to desired course. Results shown include the G-1/Collins and Butler data acquired at the FAA Technical Center using precision tracking radar as well as flight test results from the operational experiments of the A.C. 500/King System using ARTS III radar. Also included on this figure are the results of the West Coast Loran-C Flight tests which used a precision, multiple DME position reference. These measured TSCT errors are plotted against RSS computed TSCT error for the same data. The RSS computations were based on airborne measurements of sensor, computer and flight technical error components. The results shown clearly indicate that for measured total system errors greater than 1.0 nm the RSS technique is more than 30% conservative. The results also indicate a general trend for less data scatter and less conservatism for the G-1/Collins results (airline quality system) compared to the G-1/Butler or the A.C. 500/King results. However, the percent conservatism remains approximately the same for both airline quality and general aviation systems. This graphically and quantitatively answers the question about the degree of conservatism of the RSS computation. The 33% to 35% conservatism

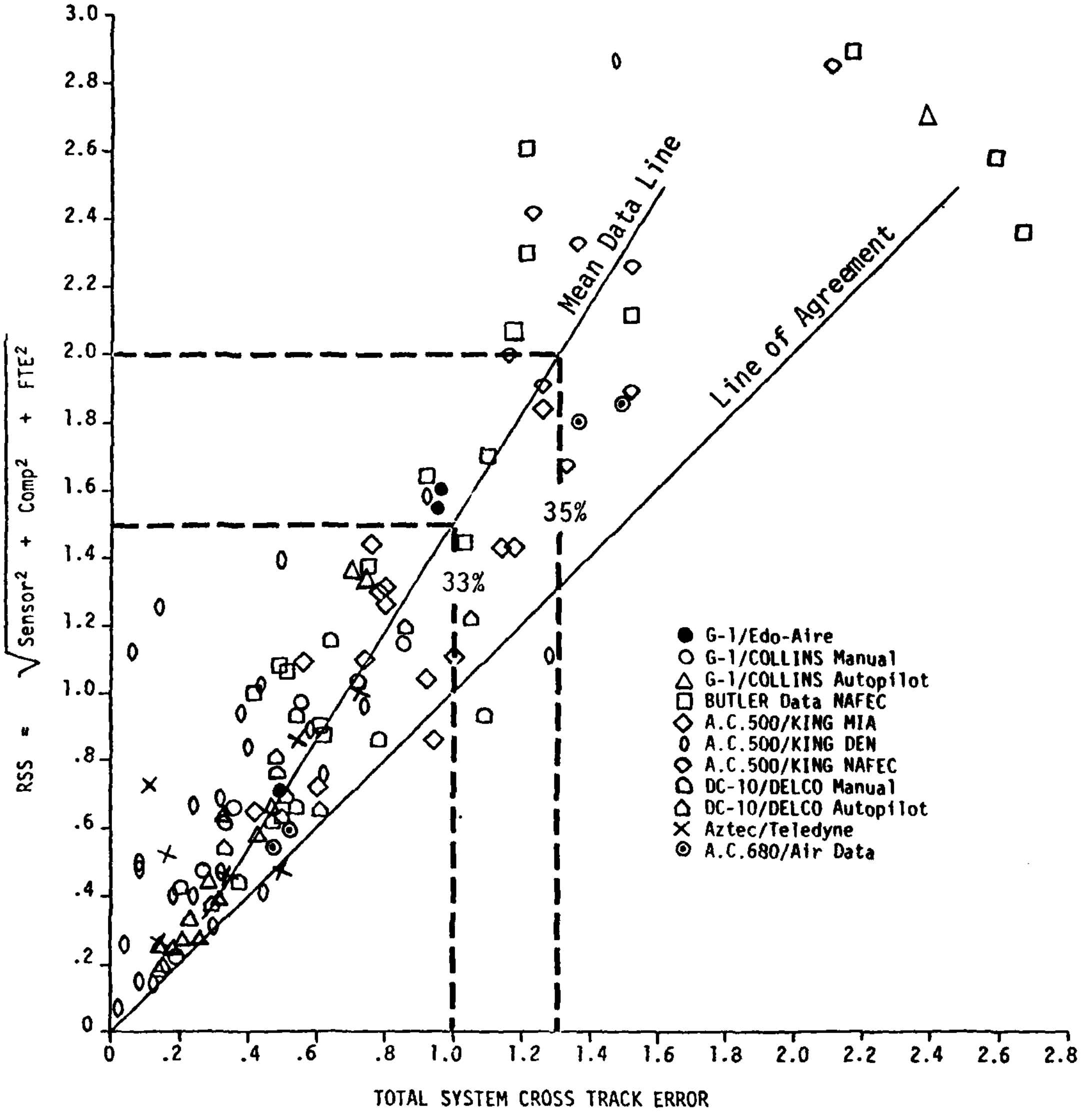


Figure 4.2 Comparison of RSS and Total System Cross Track Error for Various Levels of RNAV System Complexity

essentially provides an additional amount of buffer airspace over and above what would be supplied by a precise RSS two-sigma, 95% confidence error combination technique for TSCT. In reality, the sigma value for the current RSS technique is much higher than two due to the error dependence and correlation which produces an inflated and conservative estimate of TSCT.

Interpretation of Figure 4.2 in a slightly different manner answers the question about when a change from RSS might become a requirement. It was noted on the figure that the RSS technique resulted in computed TSCT errors 35% larger than measured at an RSS value of 2.0 nm and 33% larger than measured at an RSS value of 1.5 nm. Stated another way, when the RSS computation indicated that the flight tested system was capable of operating with 2.0 nm two-sigma route widths, the actual measured two-sigma TSCT accuracy was ±1.3 nm. This ±1.3 nm performance may appear somewhat unrepeatable based on the data scatter of Figure 4.2. However, it should be recalled that the aggregation of 199 flights shown in Table 3.4 showed a ±1.04 nm two-sigma route width capability. The two-sigma capability represented by this data may be assumed to correspond to a 95% probability that all aircraft will be within the ±1.04 nm route width. Although the experimental data contained slightly more data in the extreme tail of the normal distribution, additional statistical editing would conventionally disregard such data. For example, the one-sigma data bandwidth corresponded exactly to a 68% probability while the two-sigma data bandwidth was slightly less than the 95% probability number. Since editing was performed from operational rather than mathematical considerations, the distribution was close enough to 95% probability to be considered acceptable. Further editing could be performed to make the two-sigma and 95% probability values identical as were the one-sigma/68% numbers. This cross validation of the conservatism of the RSS technique is quite impressive. The reason for the large scatter shown in the figure is that it was desired to show the computed and measured TSCT comparison on an individual route segment basis across several flights. This introduces more scatter, especially in the VOR and FTE statistics

due to signal noise, scalloping and cockpit workload variations on individual segments.

At a computed TSCT accuracy of ±1.5 nm, the conservatism is about 33%. Measured TSCT at this point was ±1.0 nm two-sigma. This leads to the implication that a change from the RSS may be necessary. Specifically, as stated earlier, the RSS technique has been applied acceptably and is currently compatible with a ±2.0 nm route width requirement. The current RNAV system design certification tables of AC 90-45A are based on the RSS technique. The ±2.0 nm route width is generally used for airspace planning and designing RNAV procedures. However, if a change in the ±2.0 nm route width becomes a regulatory necessity, then the conservatism of the RSS technique may become an unnecessary luxury. That is to say that more accurate techniques for error combination may be required for both system certification and airspace planning purposes.

4.2 ERROR COMBINATION TECHNIQUES SUITABLE FOR FURTHER SUBSTANTIATION

The most suspect basic RSS assumption is that the TSCT errors are uncorrelated and independent. The basic reasons for suspecting error correlation have been previously discussed. In addition, based on empirical results, the 33% to 35% conservatism indicated for the RSS technique verifies the suspicion that a negative correlation may exist between some of the error budget elements. For this reason, an examination of incorporating correlation terms into the RSS computational technique, and establishing possible magnitudes for the correlation terms, was initiated. First, the basic approach will be described. Then the approach will be illustrated for two levels of RNAV equipment. <u>Although preliminary indications regarding the technique are quite positive, the following analysis is only an illustration of the plausibility and is not intended to represent a detailed evaluation and substantiation.</u>

For uncorrelated, independent error sources the RSS computation technique illustrated in equation (1) is valid. This equation can be simplified if the ground and airborne VOR and DME components are combined into a "sensor" or "radio" error quantity. Equation (1) then becomes:

$$\sigma^2_{TSCT} = \sigma^2_{Sensors} + \sigma^2_{Computer} + \sigma^2_{FTE} + \sigma^2_{CSE} \qquad (2)$$

or

$$\sigma^2_{TSCT} = \sigma^2_{NS} + \sigma^2_{FTE} \qquad (3)$$

where σ_{NS} = measured navigation system error which includes sensor input, computer signal smoothing and filtering, RNAV computer error, and course selection error.

If, however, the errors are correlated, then using the RSS technique is not valid and equations must be developed which include sufficient cross correlation terms to account for the differences previously indicated between computed and measured TSCT errors, σ_{TSCT} in this case.

The correlation coefficient ρ is generally defined as the quantitative measure of association between variables. When ρ is 1.0 perfect positive correlation exists. When ρ is zero there is no correlation and when ρ is -1.0 perfect negative correlation between the variables being examined is indicated. Considering systems not requiring manual course selection and including the correlation coefficient between navigation system errors (also called airborne equipment error) and FTE, equation (3) becomes:

$$\sigma^2_{TSCT} = \sigma^2_{NS} + \sigma^2_{FTE} + 2\rho_{NF}\,\sigma_{NS}\,\sigma_{FTE} \qquad (4)$$

where

ρ_{NF} = the correlation coefficient between navigation system and FTE errors

and the equation normally used for computing the value of ρ_{NF} is

$$\rho_{NF} = \frac{\text{Covariance of NAV system and FTE}}{\text{square route of the product of variances of NAV system and FTE}}$$

$$\rho_{NF} = \frac{\text{Covariance (N.S., FTE)}}{(\sigma^2_{NS} \times \sigma^2_{FTE})^{1/2}} \qquad (5)$$

Similarly, including the correlation coefficients in the more detailed error combination equation (2) results in equation (6)

$$\sigma^2_{TSCT} = \sigma^2_{SENS} + \sigma^2_{COMP} + \sigma^2_{FTE} + 2\rho_{SC}\sigma_S\sigma_C + 2\rho_{CF}\sigma_C\sigma_F + 2\rho_{SF}\sigma_S\sigma_F \quad (6)$$

where

ρ_{SC} = correlation coefficient between sensor and computer errors

ρ_{CF} = correlation coefficient between computer error and FTE

ρ_{SF} = correlation coefficient between sensor errors and FTE

It can be seen that the incorporation of correlation coefficient terms quickly leads to a high degree of complexity in the calculation of total system crosstrack performance. In fact, if equation (1) were expanded to include all possible correlation terms, fifteen correlation coefficients would result. The current evaluation of alternative error combination techniques was aimed at resolving the problem of RSS conservatism previously specified while keeping the complexity of the error combination and correlation analysis to a straightforward technique which would yield the desired accuracy. For reasons of simplicity, therefore, the analysis was initiated using equation number (4).

As a first step in the evaluation of the correlation between navigation system error (all equipment errors associated with the airborne navigation system) and FTE (the crosstrack steering error) the overall data sets from four of the flight test programs were investigated. Table 4.1 summarizes the number of flights (samples) and the calculated FTE correlation with NAV system errors for each of these four experiments. The King data was broken down into two subsets due to the diversity of routes, traffic and test pilots sampled in the two operational experiments.

Upon initial investigation, the tabulated values for ρ_{NF} indicate two trends. First, the correlation is apparently negative for all the experiments with greater than 14 flights. Second, there seems to be a difference in correlation significance between the airline quality and the general aviation navigation systems. In order to explore the latter trend, and to obtain some insight as to the meaning of the magnitudes of negative correlation indicated in the table, a more detailed statistical analysis is required.

Table 4.1 Correlation Coefficient Summary For Four Flight Test Programs

RNAV System	Application	No. of Flights	Correlation Coefficient (NAV System to FTE) ρ_{NF}
COLLINS	Airline	28	-0.1[2]
KING	General Aviation		
MIA		23	-0.7[1]
DEN		14	-0.4
BUTLER	General Aviation	45	-0.5[1]
DELCO	Airline	3	+0.2[2]
TELEDYNE	General Aviation	21	-0.7[1]

/<u>Note</u>/ 1. Strong negative correlation is indicated (see Table 4.2.

2. No correlation exists (see Table 4.2).

The correlation coefficient, ρ_{NF}, can also be interpreted as an indication of the reliability of the association between correlated variables.

The range of ρ_{NF} can be from -1 to +1, depending on the degree of association. Table 4.2 can be used to determine the significance of the correlation coefficient computed from a sample at a certain confidence level. This table provides the maximum values of ρ which can be expected by chance alone when actually no correlation exists. The 95% confidence level indicates there is only a 5% chance of having ρ as large as those in the table when no correlation exists. In order to conclude at a given confidence level that the correlation does exist, the calculated ρ should exceed the tabulated value of ρ.

Examination of Table 4.2 verifies the footnoted conclusions indicated on Table 4.1. That is, the King (MIA), the Butler, and the Teledyne general aviation data shows a strong negative correlation exists between navigation system errors and FTE. The 99% confidence level values of Table 4.2 are exceeded by a significant amount for all

Table 4.2 Values of Correlation Coefficient, ρ*

No. Plts	95% Confidence level				99% Confidence level				
	Total number of variables				Total number of variables				
	2	3	4	5	2	3	4	5	
1	.997	.999	.999	.999	1.000	1.000	1.000	1.000	1
2	.950	.975	.983	.987	.990	.995	.997	.998	2
3	$\boxed{.878}$	.930	.950	.961	$\boxed{.959}$	.976	.983	.987	3
4	.811	.881	.912	.930	.917	.949	.962	.970	4
5	.754	.836	.874	.898	.874	.917	.937	.949	5
6	.707	.795	.839	.867	.834	.886	.911	.927	6
7	.666	.758	.807	.838	.798	.855	.885	.904	7
8	.632	.726	.777	.811	.765	.827	.860	.882	8
9	.602	.697	.750	.786	.735	.800	.836	.861	9
10	.576	.671	.726	.763	.708	.776	.814	.840	10
11	.553	.648	.703	.741	.684	.753	.793	.821	11
12	.532	.627	.683	.722	.661	.732	.773	.802	12
13	.514	.608	.664	.703	.641	.712	.755	.785	13
14	.497	.590	.646	.686	.623	.694	.737	.768	14
15	.482	.574	.630	.670	.606	.677	.721	.752	15
16	.468	.559	.615	.655	.590	.662	.706	.738	16
17	.456	.545	.601	.641	.575	.647	.691	.724	17
18	.444	.532	.587	.628	.561	.633	.678	.710	18
19	.433	.520	.575	.615	.549	.620	.665	.698	19
20	.423	.509	.563	.604	.537	.608	.652	.685	20
21	$\boxed{.413}$	.498	.552	.592	$\boxed{.526}$	.596	.641	.674	21
22	.404	.488	.542	.582	.515	.585	.630	.663	22
23	$\boxed{.396}$	.479	.532	.572	$\boxed{.505}$	.574	.619	.652	23
24	.388	.470	.523	.562	.496	.565	.609	.642	24
25	.381	.462	.514	.553	.487	.555	.600	.633	25
26	.374	.454	.506	.545	.478	.546	.590	.624	26
27	.367	.446	.498	.536	.470	.538	.582	.615	27
28	$\boxed{.361}$	.439	.490	.529	$\boxed{.463}$	.530	.573	.606	28
29	.355	.432	.482	.521	.456	.522	.565	.598	29
30	.349	.426	.476	.514	.449	.514	.558	.591	30
35	.325	.397	.445	.482	.418	.481	.523	.556	35
40	.304	.373	.419	.455	.393	.454	.494	.526	40
45	$\boxed{.288}$	.353	.397	.432	$\boxed{.372}$	.430	.470	.501	45
50	.273	.336	.379	.412	.354	.410	.449	.479	50
60	.250	.308	.348	.380	.325	.377	.414	.442	60
70	.232	.286	.324	.354	.302	.351	.386	.413	70
80	.217	.269	.304	.332	.283	.330	.362	.389	80
90	.205	.254	.288	.315	.267	.312	.343	.368	90
100	.195	.241	.274	.300	.254	.297	.327	.351	100
125	.174	.216	.246	.269	.228	.266	.294	.316	125
150	.159	.198	.225	.247	.208	.244	.270	.290	150
200	.138	.172	.196	.215	.181	.212	.234	.253	200
300	.113	.141	.160	.176	.148	.174	.192	.208	300
400	.098	.122	.139	.153	.128	.151	.167	.180	400
500	.088	.109	.124	.137	.115	.135	.150	.162	500
1,000	.062	.077	.088	.097	.081	.096	.106	.116	1,000

*/Note/ Taken from Reference 19 Table A-49.

of these data sets. The King/DEN data does not demonstrate with 99% confidence that a correlation exists, but the $\rho_{NF} = -0.4$ test result is acceptably close to the 95% confidence level to warrant further investigation when the other King and the Butler data trends are considered. Finally, the ρ_{NF} correlation does not apparently apply to the more sophisticated airline quality RNAV systems of the Collins and Delco types. This difference in results for G.A. and airline systems might have been expected considering the more sophisticated software and the more accurate receivers generally associated with the airline systems.

The error correlation analyis must diverge at this point. First, the present, simplified technique will be explored in more detail for the King (MIA and DEN) results. This will be done to verify on a route segment by route segment basis across several flights that the negative correlation indicated for general aviation systems by overall test results is not a random occurrence. Rather it will be shown that the use of a negative ρ_{NF} (value to be determined) is a reasonable technique for computing total system error for general aviation systems based on NAV system and FTE error components. Following this more detailed analysis of the general aviation results will be a summary of the correlation trends for airline quality navigation systems derived from analysis of the Delco data.

4.3 GENERAL AVIATION NAVIGATION SYSTEM ERROR CORRELATION

The route segment statistics used for more detailed NAV system and FTE correlation analysis were the results of the operational flight test performance in Denver and Miami. These results were chosen because the highest confidence level that a correlation existed was observed in the Miami data while less than a 95% confidence level that a correlation existed was observed in the Denver data. Further examination of these two data sets permits a value judgement to be made based on a more in depth analysis. The value judgement in question is whether or not a correlation coefficient, ρ_{NF}, can be established which will permit more reliable prediction of the measured total system crosstrack error. By choosing two data sets showing different levels of possible correlation

from an overall statistical aggregation, the repeatability and reliability of the correlation coefficient magnitude can be established.

The correlation coefficient (ρ_{NF}) between navigation system error and FTE was calculated across all the flights occurring on each route segment in the Miami and Denver tests.[11] The Miami results had the highest number of flights (12) per segment and the fewest number of route segments (7). Data was subdivided into "To" and "From" modes which lead to fourteen calculated ρ_{NF} values. The negative ρ_{NF} values ranged from -0.33 to -0.850 indicating a significantly reliable negative correlation. Although the magnitude of the correlation coefficient was somewhat unrepeatable segment to segment, ρ_{NF} for 8 of the 14 route segments or 56% of the data was between -0.730 and -0.850.

Figure 4.3 is a graphical summary of the Miami and Denver route segment correlation coefficients. It should be remembered that on an overall experiment basis, the Miami results indicated a more reliable correlation than the Denver data.

The Denver data consisted of a total of 14 flights. These flights were divided over 3 STARs and data distribution varied due to ATC requests. Some route segments only included 2 flights while others included 5. This small number of flights per segment could account for the more scattered ρ_{NF} values calculated in Figure 4.3. The basic range of the data scatter band was, however, very close to that of the Miami data. Minimum ρ_{NF} was -0.355 while maximum was -0.979. The accuracy and reasonableness of assuming an approximate value of ρ = -0.7 are illustrated in Figure 4.3 and 4.4. These two figures show that although a constant value of ρ = -0.7 is only approximate, the 33-35% RSS conservatism can be accurately reduced. Using this technique the modified RSS computation accurately predicts measured TSCT.

The results of this preliminary analysis of NAV system error and FTE correlation are quite encouraging. The general aviation data investigated seems to show a reliable tendency (95% confidence level) that a negative correlation exists. However, the magnitude of the correlation coefficient ρ_{NF} varies from -0.33 to -0.98. This data

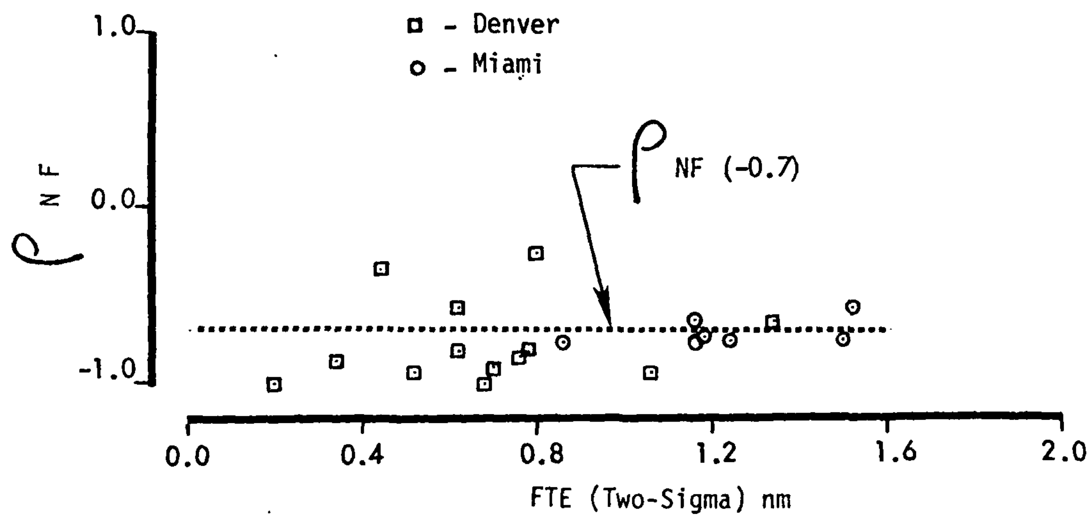


Figure 4.3 Correlation Coefficient vs. FTE (Two-Sigma in nm) for a General Aviation Navigation System

scatter precludes a firm recommendation of a specific value for ρ_{NF} at this time. Current data analysis should be expanded to include additional systems. Sample size (number of flights) appears to have a direct impact on data repeatability with the 12 flights per route segment being a minimum. It does appear that using a modified RSS computation technique which includes consideration of the correlation between NAV system errors and FTE will improve the accuracy with which total system crosstrack error can be predicted. The recommended error combination equation is:

$$\sigma^2_{TSCT} = \sigma^2_{NS} + \sigma^2_{FTE} + 2\rho_{NF}\,\sigma_{NS}\,\sigma_{FTE}$$

In this equation ρ_{NF} would be a specified constant, the value of which has not been sufficiently evaluated at this time. FTE error budget values or manufacturer demonstrated FTE values could be used along with measured navigation system error to more reliably predict total system performance for General Aviation navigation systems.

4.4 AIRLINE NAVIGATION SYSTEM ERROR CORRELATION

The type of error correlation discussed for general aviation RNAV systems in Section 4.3 does not apparently apply to airline quality

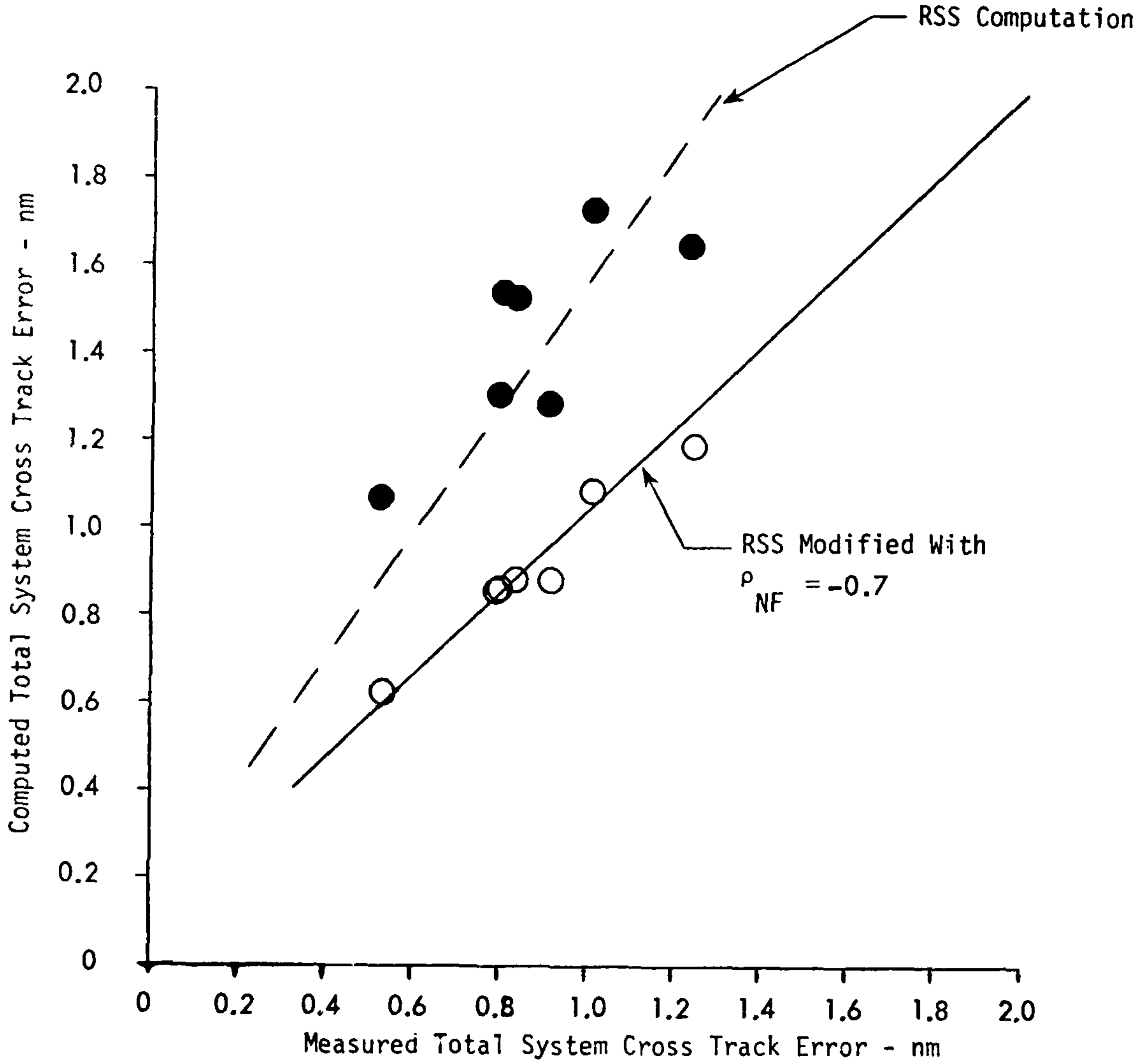


Figure 4.4 Measured RNAV Accuracy Vs. Modified RSS Computed Accuracy

systems. As shown in Table 4.1 of that section, the correlation coefficient between navigation system errors and FTE was near zero, indicating no reliable correlation existed. This was true for both the Collins and the Delco flight test data. This result is not at all surprising since there are several additional levels of filtering and smoothing inherent in both the systems tested and in airline avionics systems in general. Specifically, the VOR receivers and DME interrogators certified in conjunction with the Collins and Delco RNAV computer are generally of a higher quality than general aviation equipment. Secondly, both the airline RNAV systems tested employ signal smoothing algorithms within the RNAV computer. Finally, airline operations routinely provide a flight director. This navigation aid further smooths the output guidance displayed to the pilot when compared to the simple CDI or HSI deflection presented to the general aviation pilot. It is for these reasons - more accurate receivers, more sophisticated filtering and signal processing and more complex displays - that the simple correlation between navigation system errors and FTE does not apply to airline quality RNAV systems. It is also for these reasons that the more complex error combination equation is indicated to adequately sort out the more subtle correlations involved. The equation to be investigated was shown as Equation (6) in Section 4.2. This equation includes error correlation terms for sensor and computer, computer and FTE, and finally between sensor and FTE. In the most general case, this equation takes the form of:

$$\sigma^2_{TSCT} = \sigma^2_{SENS} + \sigma^2_{COMP} + \sigma^2_{FTE} + 2\rho_{SC}\sigma_S\sigma_C + 2\rho_{CF}\sigma_C\sigma_F + 2\rho_{SF}\sigma_S\sigma_F \quad (7)$$

where

ρ_{SC} = correlation coefficient between sensor and computer errors

ρ_{CF} = correlation coefficient between computer error and FTE

ρ_{SF} = correlation coefficient between sensor errors and FTE

The estimate of two-sigma total system crosstrack errors over a series of flights of a given RNAV system is the desired goal. Therefore, the Delco analysis was continued by aggregating statistics across three

manual flights using enroute data. Unfortunately, this small sample size precludes utilization of the statistics of reliable (95% confidence level) estimates. However, this being the only data base available, it was used to reinforce the trends of error correlation noted during individual flights. Table 4.3 is shown to document these trends.

In Table 4.3 the cross flight statistical data is shown for three types of data editing. Overall data (3) indicates all recorded data was processed. Scalloping Area (1) indicates that these are the results obtained in the environment characterized by VOR signal scalloping. Column (2) contains the data aggregated from unscalloped VOR regions. Regarding the ρ_{SC}, ρ_{CF} and ρ_{SF} being explored, Table 4.3 verifies the fact that correlation exists between the indicated variables. However, this table shows stronger correlation coefficients for other variable combinations such as RNAV system and equipment. Current results can be interpreted to mean that correlations are indicated between several error sources. This means that a more complex error combination computation will be required as indicated by the form of Equation (7). However, the current limited data base is not sufficient to isolate the specific error sources. This precludes calculation and utilization of a limited number of applicable correlation coefficients. The error correlation analysis for airline quality RNAV systems will be carried one step further simply to illustrate the validity of the current analytical approach.

If all of the cross correlation terms are included in the RSS analysis, then the computation of total system crosstrack from all the measured errors will result in an exact prediction of measured total system error. That is, the covariance terms are calculated using data from the same population that was used to obtain the total measured system error. In other words, the total error must equal the sum of the contributing parts.

Table 4.4 summarizes the cross flight results for the manual flights. The combination techniques of RSS and RSS modified by covariance terms are compared to the recorded total system crosstrack error. Segregating the scalloped and non-scalloped regions as well as combining them is shown for comparison. Although this data represents only three flights,

Table 4.3 Summary of Cross Flight Statistical Data For An Airline Navigation System [11]

ORD→DEN

		Cross Flt. Statistics of J867 2/28, 6/4, and 6/12 (1)	(2)	(3)
μ	FTE	0.0943	0.0262	0.0430
	RNAV	0.2427	-0.2653	-0.1395
	EQUIP	-0.0834	-0.3526	-0.2860
	SYSTEM	0.3371	-0.2390	-0.0964
	COMP	0.3261	0.0874	0.1465
σ	FTE	0.2234	0.0907	0.1390
	RNAV	0.6781	0.3452	0.5012
	EQUIP	0.8094	0.3234	0.5035
	SYSTEM	0.7152	0.3710	0.5402
	COMP	0.5986	0.2816	0.3978
σ	FTE/RNV	0.0009	0.0051	0.0107
	FTE/EQ	-0.0618	-0.0061	-0.0162
	FTE/SYS	0.0508	0.0133	0.0300
	FTE/COMP	0.0627	0.0112	0.0269
	RNV/EQ	0.3783	0.0723	0.1732
	RNV/SYS	0.4607	0.1243	0.2618
	RNV/COMP	0.0815	0.0469	0.0779
	EQ/SYS	0.3166	0.0661	0.1570
	EQ/COM	-0.2768	-0.0324	-0.0803
	SYS/COMP	0.1441	0.0582	0.1048
ρ	FTE/RNV	0.0061	0.1624	0.1531
	FTE/EO	-0.3416	-0.2087	-0.2315
	FTE/SYS	0.3182	0.3957	0.3993
	FTE/COMP	0.4688	0.4389	0.4859
	RNV/EQ	0.6893	0.6472	0.6865
	RNV/SYS	0.9500	0.9704	0.9671
	RNV/COMP	0.2007	0.4827	0.3910
	EQ/SYS	0.5468	0.5912	0.5773
	EQ/COMP	-0.5714	-0.3553	-0.4008
	SYS/COMP	0.3367	0.5567	0.4878

(1) Scalloping Area

(2) Remaining Area

(3) Overall

Table 4.4 Comparison of Error Combining Techniques Across Flights For Airline Systems

CROSS FLIGHT STATISTICS OF 2/28, 6/4, 6/12	SYSTEM XTRK ERROR σ	RSS WITH ALL COVARIANCE TERMS σ	RSS σ
SCALLOPING AREA	0.715	0.715 (0.715)	1.031 (0.714)
REMAINING AREA	0.371	0.371 (0.371)	0.438 (0.357)
OVERALL	0.540	0.540 (0.540)	0.657 (0.520)

( ) Number Based on σ_{FTE} and σ_{RNAV} Only

the expected results are verified. The RSS technique, including the cross correlation terms, predicts the total system error significantly better than using the simple RSS technique. Again, the RSS technique including the covariance terms provide an exact prediction of the total system error.

The overall result of this evaluation of the RSS error combination technqiue and possible alternatives has resulted in a better understanding of the relationship between computed and measured navigation total system accuracy. The results of this analysis have shown that the RSS technique is overly conservative for two reasons. First of all, error correlation was identified between FTE and other error sources which invalidates one of the basic RSS assumptions. Secondly, regardless of system type, system complexity, system absolute accuracy, or the navigation mode (manual or autopilot), the flight test results showed FTE to be of the same order of magnitude as TSCT, which precludes application of the RSS error combination technique. When a system demonstrated a 0.3 nm total system accuracy, the measured FTE was 0.2 nm. Similarly, when an RNAV system demonstrated a 1.5 nm total system accuracy, measured FTE was 1.4 nm. As a result of the similar magnitudes of FTE and actual TSCT,

the RSS technique computed estimates of TSCT were 20% and 35% conservative for respective measured total system accuracies of 0.3 nm on the Collins system and 1.3 nm on the King system. This degree of conservatism was found to be acceptable only in the ±2.0 nm route width environment. <u>If total system accuracy tolerances are reduced and the need for more efficient airspace utilization is demonstrated, then a more accurate total system error computation should be required for demonstration of navigation system compliance</u>.

In anticipation of the requirement for a more accurate analytical computation of total system accuracy, an alternative technique was investigated which employed the use of a correlation coefficient. The correlation coefficient defines the quantitative relationship between two variables and is then included in the error combination technique. Preliminary analysis has shown that a strong negative correlation exists between FTE and RNAV system error for general aviation systems. However, analysis of the airline quality digital system data did not produce the same strong correlation, due to limitations of the available airline data and time constraints on the analysis, the usefulness of the correlation coefficient technique on this level cf system must be investigated futher.

4.5 THE IMPORTANCE OF FTE

Previously, FTE was simply another RNAV error budget element which was used by manufacturers to demonstrate compliance per Advisory Circular 90-45[20], and by airspace planners to provide sufficient route separation per Handbook 7110.18[21]. Error budget elements were assumed to be independent and normally distributed, and total system errors were computed in a root sum square (RSS) fashion. That is, the standard deviations obtained from the various ground and airborne error sources were combined algebraically as previously discussed in Section 4.4. In establishing a system's performance, a system designer or airspace planner could trade off reduction in the errors of any of the airborne elements, providing the specified total system accuracy was not exceeded. Based on the issuance of Advisory Circular 90-45A[1], <u>the benefits</u>

of this error combination and trade off technique are no longer available except for a special class of RNAV systems.

Table 4.5 presents the breakdown of RNAV system classification, FTE error budget values and accuracy criteria by navigation system type (1), (2) and (3) as defined previously. The RNAV system classification is a direct quote from Appendix A, Section 2 of AC 90-45A. According to this document, category (1) systems must demonstrate that: "The total of the error contributions of the airborne equipment (receivers plus area navigation - including desired track setting as well as waypoint setting errors) when combined RSS with the following specific error contributions should not exceed the error values shown in Table 1, Appendix A." The specific error contributions referred to are a ±1.9° VOR ground station error and a ±0.1 nm DME ground station error. Table 1 of Appendix A[1] was generated using these ground station error elements along with the following assumptions for airborne error elements:

VOR airborne	3.0°
DME airborne	3% or 0.5 nm
RNAV system	0.5 nm (including computer and "manual" OBS errors)
Pilot	Zero

Type (1) systems can only trade off airborne error elements from the RNAV system with the VOR receiver error or DME interrogator error. The magnitude of this limitation to the system designer can be assessed by comparing Table 1, Appendix A[1] with Table 2, Appendix D[1] (for use by the airspace planner) which includes the following error elements:

Ground	
VOR	1.9°
DME	0.1 nm
Airborne	
VOR	3.0°
DME	3% or 0.5 nm
RNAV System	0.5 nm
Pilot	
Crosstrack	2.0 nm
Alongtrack	Zero

TABLE 4.5 FTE REQUIREMENTS Per AC 90-45A

Type	RNAV SYSTEM CLASSIFICATION [1]	FTE Error Budget	Accuracy Criteria
(1)	"2-D RNAV system using reference facility for continuous navigation information" (implies use of the published or charted VORTAC station)	Zero	Appendix A Table 1 Page 15
(2)	"2-D RNAV systems which use VOR/DME information from other than the reference facility" (implies RNAV systems using a station selection algorithm and/or some type of computational priority selection or filter)	Either Zero, or 1.0 nm Enroute 1.0 nm Terminal 0.5 nm Approach	Either Table 1, or 2.5 nm Enroute 1.5 nm Terminal 0.6 nm Approach (whichever is greater)
(3)	"2-D RNAV system not using VOR/DME for continuous navigation information" (applies to VLF, Omega, Loran, Inertial, etc.)	2.0 nm Enroute 1.0 nm Terminal 0.5 nm Approach	2.5 nm Enroute 1.5 nm Terminal 0.6 nm Approach

/Note/
(a) All Table and Appendix references pertain to AC 90-45A.
(b) AC 90-45A specifies use of the RSS error combination technique for determination of total system error from FTE and other error budget elements.
(c) Accuracy criteria are specified for the cross track deviation only in this table. AC 90-45A includes both along track and cross track error limits.

Figure 4.5 illustrates the magnitude of the effect of a 2.0 nm FTE error element on crosstrack RNAV accuracy for enroute navigation with a tangent point distance of 50 nm. The area between the upper and lower limits is designated "Residual Error" and varies from 1.0 nm at 0 nm alongtrack to 0.2 nm at an alongtrack distance of 130 nm. The term "residual error" was chosen to designate the current difference which exists between the compliance criteria for Type (1) RNAV systems and the enroute waypoint displacement area considered for each waypoint when developing RNAV routes and procedures. This residual error is no longer available to the RNAV system designer as an error element trade off or "kitty". Rather, the residual error can be used by the FAA when evaluating ground station accuracy requirements or reduced width capabilities.

Type (2) systems "must show that the algorithm used will always select a station that will provide crosstrack/alongtrack errors equal to or less than the greater of the RNAV system errors of the reference facility for any RNAV track (Table 1) or the errors shown in paragraph 2.a(3)"[1]. The latter errors correspond to 2.5 nm enroute, 1.5 nm terminal and 0.6 nm for final approach. Referring again to Table 4.5, the FTE error budget consistent with this requirement is either zero as for Type (1) systems or 2.0 nm enroute, 1.0 nm terminal and 0.5 nm approach. However, the wording of the AC 90-45A requirement specifies compliance with whichever error limit is "greater". This essentially results in use of the Table 1 limits since the error tolerances of Table 1 exceed the maximum enroute tolerance of 2.5 nm once an alongtrack distance of 40 nm is exceeded or a tangent point distance greater than 80 nm is used. For practical purposes, Type (2) systems will primarily certify using the Table 1 error limits and zero FTE. Therefore, the comments relevant to Type (1) system design and error budgeting apply also to Type (2) systems.

To provide further insight into the differences in crosstrack accuracy limits (residual error) with and without FTE, Table 4.6 is provided. This table indicates the trend of the difference between the accuracy limits for airspace planning for both enroute and terminal area route design and what the sytem designer must comply with for both applications. It can be seen that with a 2.0 nm FTE error budget (enroute),

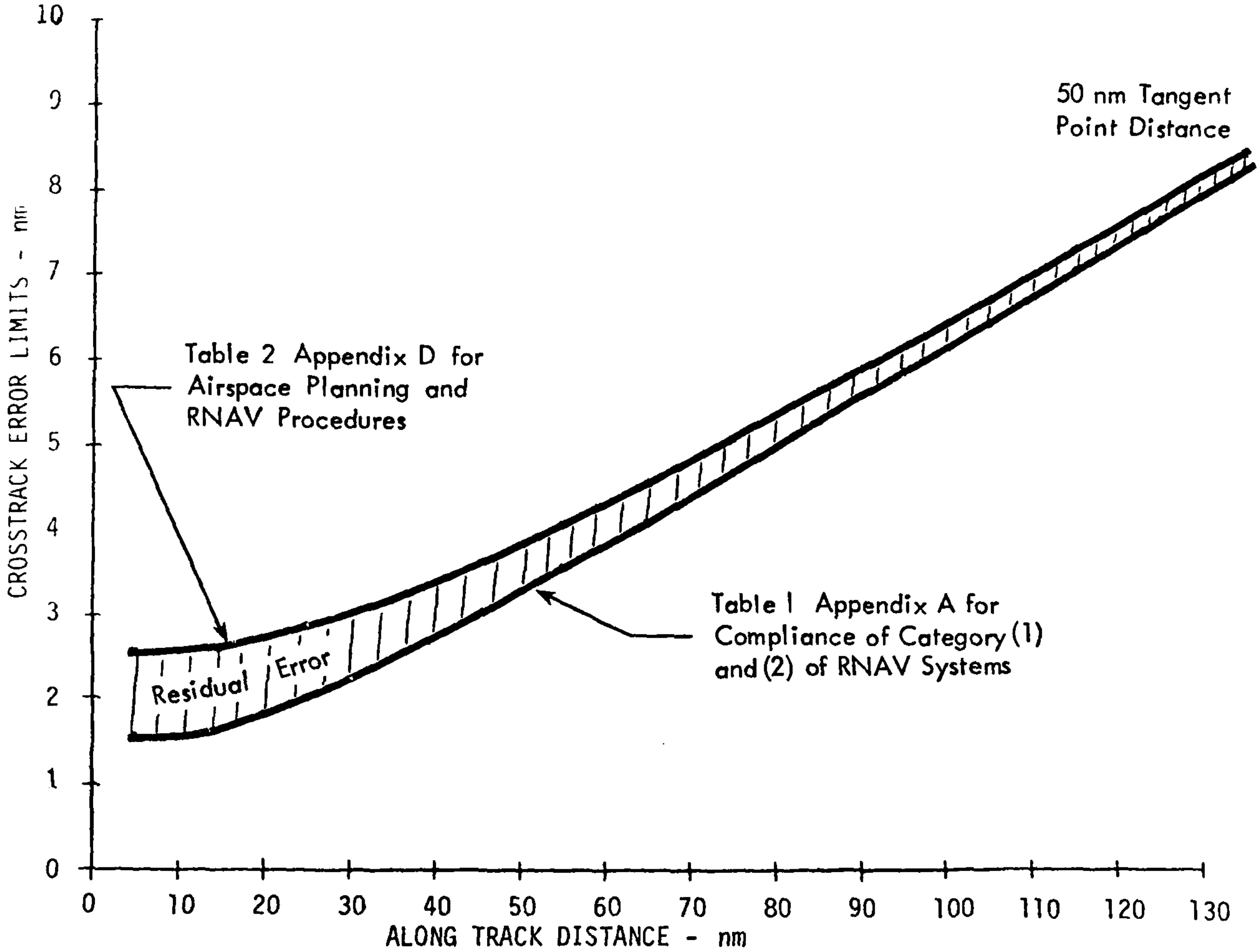


Figure 4.5 Residual RNAV Error Component Due to Computed Total System Error with Zero FTE (Compliance) and 2.0 nm FTE (Airspace Planning)

TABLE 4.6 <u>DIFFERENCES IN CROSS TRACK ACCURACY WITHOUT FTE</u>
(Incomplete Tables - To Illustrate Trends)

Perpendicular Distance to Tangent Point	Distance Along Track From Tangent Point: 0	10	20	30	40	50	60	130
0	-	1.7	1.2	0.9	0.7	0.6	0.5	0.2
10	1.8	1.3						
20	1.7		1.0					
30	1.5			0.8				
40	1.2				0.6			
50	1.0					0.5		
100	0.6							
130	0.5	0.5	0.5	0.4				0.2

Less Than 0.5

2.0 nm FTE Budget vs Zero FTE Budget

Perpendicular Distance to Tangent Point	Distance Along Track From Tangent Point: 0	10	20	30	40	50	100
0	-	0.7	0.4	0.3	0.2	0.2	0.1
10	0.8	0.6					
20	0.7						
30	0.5						
40	0.3						
50	0.3						
100	0.2						0.0

Less Than 0.5

1.0 nm FTE Budget vs Zero FTE Budget

crosstrack accuracy differences of 0.5 nm to 1.3 nm exist within a 100 nm circle of the station (shaded area). Differences in crosstrack accuracy in excess of 1.0 nm occur within 25 nm alongtrack for tangent point distances from 0 to 50 nm. In contrast, if a 1.0 nm FTE budget value is used, the difference in crosstrack accuracy utilized by the airspace planner and demonstrated by the system manufacturer is reduced to 0.5 nm or less over the major portion of the terminal area operating regime (area designated by diagonal lines).

Type (3) RNAV systems are handled somewhat differently. These systems must certify to constant accuracy limits of 2.5 nm enroute, 1.5 nm terminal and 0.6 nm final approach. "The total of the error contributions of the airborne equipment (including update, aircraft position and computational errors) when combined with appropriate flight technical errors" should not exceed the accuracy limits listed "with 95% confidence (2-sigma) over a period of time equal to the update cycle". The FTE errors referred to are listed in Table 4.5 for Type (3). The impact of this compliance criteria is that the 2-sigma crosstrack accuracy assessment includes FTE and trade offs can be made on the system design level with FTE and other airborne error elements for category (3) RNAV systems. The basic error budget available for other airborne elements can be derived using the equation:

$$\sigma^2_{TOTAL} = [\sigma^2_{RNAV} + \sigma^2_{FTE}]^{1/2}$$

Inserting the specified values for σ_{total} and σ_{FTE}, and solving the RNAV system error budget limits result in:

Airspace	2σ RNAV System Error Limits
Enroute	1.5 nm
Terminal	1.12 nm
Approach	0.33 nm

To summarize what has been discussed, flight technical error remains an important error budget element for the design and utilization of airpace as designated in Appendix D of AC 90-45A. FTE also remains

an explicit error budget element within that same document for Type (3) RNAV system design and certification pruposes (This is the category within which Loran-C, Omega, Omega/VLF and GPS are certified). FTE is not available however, as a trade off error element for Types (1) and (2) of RNAV systems. Figure 4.5 was presented to illustrate the effect of a 2.0 nm FTE error budget value on crosstrack accuracy for enroute navigation. This figure quantifies the current discrepancy which exists between accuracy compliance criteria for Types (1) and (2) of RNAV system (as defined in AC 90-45A) and the accuracy derived from combining the error budget elements prescribed for airspace planning which include FTE (Appendix D, AC 90-45A). The magnitude of this discrepancy was shown to be as large as 1.0 nm and the terminology "residual error" was used to designate this difference. The magnitude of this residual error was shown to be directly dependent upon the value chosen for the FTE error budget (Table 4.5). For example, an FTE error budget value of 2.0 nm yields differences (between Appendix D and the Accuracy Table 1) in crosstrack accuracy in excess of 1.0 nm within a 25 nm radius of the station. In constrast, a 1.0 nm FTE error budget value reduces the discrepancy to less than 0.5 nm over the major portion of the terminal area. The presence of large differences between airspace planning accuracies and RNAV system compliance accuracies is conservative but leads to inefficient utilization of airspace. Therefore, to accurately determine the achievable crosstrack accuracy requirements and the consistent route width reduction capabilities it is extremely important to determine both whether a 2.0 nm, a 1.0 nm or a 0.5 nm FTE error budget value is appropriate, and which of these values is realistically attainable for the Type (3) (Loran-C, Omega, GPS, etc.) systems.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The major conclusions from this analysis of error budget data for advanced navigation systems can be best summarized by reference to the program objectives previously stated in Section 1.3.

<u>Criteria To Be Considered When Certifying Advanced Digital Navigation Systems</u>

- Error Budgets -

  The available and nearly available error budget data was presented and analyzed for VOR/DME RNAV, Loran-C, and Omega/VLF. A total of 19 navigation system, aircraft type, and geographic location combinations were evaluated. The overall conclusions regarding the completeness, comparability and usability of this data were:

  1. VOR/DME-RNAV: the data base is sufficient for all three airspace regimes — enroute, terminal and approach and all three user categories — air carrier, commuter/business and general aviation.
  2. Wide Area Coverage Systems: the error budget/system compliance data base question has not been adequately addressed for Loran-C, Omega, Omega/VLF or GPS. Of the 12 sets of data investigated only 3 Loran-C tests had any error budget data at all. Of these three sets of data enroute and terminal data was available from the East Coast and approach data from the West Coast and the Vermont tests.

- Error Combination -

  A detailed analysis of alternative error combination techniques was performed for the existing VOR/DME-RNAV and Loran-C error budget data. The analysis showed that:

  1. The RSS technique is conservative by 30-35% for all types of systems in all user categories.
  2. If the need for more efficient use of airspace (increased capacity) warrants a reduction in route width requirements, then a more accurate total system error computation should be required for demonstration of compliance.

3. VOR/DME-RNAV: Alternatives to the standard RSS technique were investigated for both general aviation (G.A.) and air carrier (A.C.) types of equipment. A viable technique was developed for G.A. equipment using a negative correlation coefficient for navigation system errors and FTE to modify the standard RSS equation. A more complex technique containing three cross correlation terms was used successfully for the airline equipment. However, there was not a sufficient number of flights per route segment to verify the validity of this technique.
4. Loran-C: The Loran-C error budget data for the general aviation system tested also exhibited the negative correlation between navigation system errors and FTE. Thus it appears that the modified RSS equation might apply to both VOR/DME-RNAV and wide area navigation systems. Further substantiation of this technique for Loran-C, Omega and GPS is necessary to substantiate this finding.

- System Accuracy -

  Total system errors were within AC90-45A compliance criteria for all the systems evaluated. However, the accuracy demonstrated by the Canadian Marconi Omega/VLF system required operating in a relative mode rather than the primary hyperbolic mode. Since no other Omega/VLF, Omega, or GPS data was available, and since the performance demonstrated is so dependent on the computational algorithms used, additional data is needed to verify the system accuracy to be expected from the wide area systems.

Recommended Certification Procedures For Advanced Digital Navigation Systems

Current AC90-45A area navigation system certification criteria were evaluated in depth both analytically and empirically for VOR/DME and wide area navigation systems. Important differences were

discovered in both the system performance criteria and the method in which flight technical error impacts demonstration of compliance for these two types of systems. In addition, significant differences in system dynamics were demonstrated through the analysis of how the error budget data impacts airspace planning and pilot/controller procedures. Significant differences were demonstrated in the way various system accuracies are affected by;

1. Dynamic Response
2. To-From Display Response
3. Turn Anticipation
4. Waypoint or Leg Sequencing
5. Direct-To Functions

Due to these findings it is recommended that the certification procedures being developed by the RTCA's SC-137 be considered for use during bench tests, simulation tests and flight tests for compliance of advanced digital navigation systems.

Certification Philosophy

Four different types of test procedures are necessary for demonstration of compliance. These are:

1. Bench Tests
2. Environmental Tests
3. Installed Tests
4. Operational Tests

Of these four levels or types of testing, the first category - Bench Tests - provides the best opportunity for controlled testing and the bulk of the quantitative data for system acceptance. Since it is necessary to demonstrate that the systems satisfy both functional and accuracy performance criteria for all modes of operation and since advanced multi-sensor systems, scanning systems or sophisticated filtering techniques must be tested for all different combinations of sensor inputs, a straightforward assessment of error budget data and total system accuracy statistics is not sufficient for making the approval decision. Advanced digital navigation system certification philosophy must include both static tests and dynamic tests on the bench. It is recommended that procedures being developed by RTCA's SC-137 be considered in both of these areas.

Techniques For Verifying Compliance

Detailed navigation system performance assessment techniques and procedures were discussed for satisfying — operational requirements, accuracy requirements and functional requirements. Specific recommendations included:

1. Data Requirements: From a compliance viewpoint, error budget data must include quantitative definition of at least four error quantities. These are total system error, FTE, computer error and sensor error. In addition to this steady state performance data, the system being tested must be evaluated for functional and operational compatibility using some form of dynamic test technique which evaluates software integrity for all sensor modes and for computational and filtering compatibility with other systems already approved and operating in enroute, terminal and approach airspace.
2. Analysis Techniques: Data analysis techniques for verifying compliance should not be limited to simply comparing accuracy numbers with pre-determined tabular values. Rather, compliance must consider various error interactions with real world constraints such as route widths and ATC procedures. In order to accomplish this analysis, a modified or revised error combination technique(s) must be developed and tools for evaluating system dynamic performance must be developed. Recognizing that neither the manufacturers nor the certifying agency can bear the burden of excessive flight test data collection or analysis, the system dynamic test techniques should be designed as a a part of the bench testing procedures.
3. Flight Demonstration - These tests should be limited to evaluation of the airborne equipment only. These tests should be performed in the actual operational environment and should be limited to providing a qualitative reassurance that the system can be operated safely and reliably. In addition the minimum acceptable functional performance shall be verified by these tests.

Additional Data Requirements

In order to develop the techniques and procedures needed for satisfactory demonstration of compliance for advanced digital navigation systems, a significant amount of additional flight test data is required. The data base to be developed includes error budget data, system accuracy data and dynamic response data for the following system type and airspace region combinations:

	CONUS			ALASKA
	OMEGA	OMEGA/VLF	LORAN-C	LORAN-C
Flight Hours	60	60	120	100
Geometry/Geography	4	4	8	3
Flight Segments				
- Enroute	20	20	20	20
- Terminal	40	0	0	0
- Approach	80	0	0	0
Total Flights	4	4	8	3

Each enroute segment should be a minimum of 100 nm long. Terminal area and approach segments should be on the order of 20 nm and 10 nm in length respectively. The basic flight test pattern should consist of a closed circuit which traverses the necessary geometry/geography combinations. Each test flight should traverse the circuit collecting enroute, terminal and approach data as specified in the table.

As shown in the previous section, flight technical error (FTE) is the major component comprising the error budget values. FTE is also the most difficult quantity to verify from a manufacturer's data submittal. Therefore, as an absolute minimum, additional testing of each of the system types in the airspace regions indicated is necessary to establish the relationship and magnitude of FTE to total system accuracy.

REFERENCES

1. Anonymous, "Approval of Area Navigation Systems for Use in the U.S. National Airspace System," DOT/FAA, Advisory Circular AC-90-45A, 21 February 1975.

2. Anonymous, "Federal Radionavigation Plan, Vols. I-IV," DOT/FAA, Transportation Systems Center, Report No. DOT-TSC-RSPA-80-16, July 1980.

3. Anonymous, "Minimum Operational Performance Standards For Airborne Area Navigation Equipment," Radio Technical Commission For Aeronautics, RTCA Paper No. 251-81/SC137-52, August 1981.

4. Cassel, R., "Postulated Area Navigation Operational Environment Definition," for RTCA SC-137, February 1979.

5. Sakran, F.L., "U.S. Navy Test Program for an ARINC 599 Omega Navigation System," Naval Air Test Center, Report #TM 80-2 AT, August 27, 1980.

6. Pursel, R.H., J.D. Edmonds, "A Flight Investigation of System Accuracies and Operational Capabilities of an Air Transport Area Navigation System," for Department of Transportation, Report No. FAA-RD-76-32, May 1976.

7. Logue, T.V., "An Analysis of Radio Navigation Sensor Accuracies Associated with Area Navigation (RNAV)," for Department of Transportation, Report No. FAA-RD-78-85, August 1978.

8. Edmonds, J., J. Gallagher, R. Pursel, "A Flight Investigation of System Accuracies and Operational Capabilities of a General Aviation/Air Transport Area Navigation System (RNAV)," for Department of Transportation, Report No. FAA-RD-79-120, February 1980.

9. Edmonds, J.D., R.H. Pursel, J. Gallagher, "A Flight Investigation of System Accuracies and Operational Capabilities of a General Aviation Area Navigation System," for Department of Transportation, Report No. FAA-RD-77-43, June 1977.

10. Tomsic, G.W., "Three Dimensional Area Navigation Flight Test - Error Study Using a Basic VNAV System," for Department of Transportation, Report No. FAA-RD-76-12, January 1976.

11. Adams, R.J., "An Operational Evaluation of Flight Technical Error," Systems Control Inc. (Vt) for DOT/FAA System Research and Development Service, Report No. FAA-RD-76-33, July 1975.

12. Hughes, M., R.J. Adams, "An Operational Flight Test Evaluation of a Loran-C Navigator," Systems Control, Inc. (Vt), for the DOT/USCG Office of Research and Development, Report #CG-D-9-77, March 1977.

13. Adams, R.J., J.B. McKinley, "Airborne Evaluation of the Production AN/ARN-133 Loran-C Navigator," Systems Control, Inc. (Vt), for the Department of Transportation, Report #CG-D-32-79, July 1979.

14. Pursel, R.H., "Flight Test Investigation of Loran-C for Civil Aviation Applications," Navigation, Fall 1980.

15. Lorge, F., "Loran-C Nonprecision Approaches in the Northeast Corridor," for Department of Transportation, Report #FAA-CT-80-175, July 1980.

16. Pursel, R., "Flight Test Investigation of Loran-C for Enroute Navigation in the Gulf of Mexico," Federal Aviation Administration Technical Center, Department of Transprotation, Report #FAA-RD-80-47, September 1980.

17. Scalise, T.E., E.H. Bolz, E.D. McConkey, "West Coast Loran-C Flight Test," Systems Control, Inc. (Vt), for Department of Transportation, Report #FAA-RD-80-28, March 1980.

18. Anonymous, "CMA-734 Omega/VLF Navigation System Flight Data Summary," Canadian Marconi Company, March 17, 1980.

19. Lipson, Charles and Sheth, N.J., "Statistical Design and Analysis of Engineering Experiments," McGraw-Hill, Inc., 1973.

20. Anonymous, "Advisory Circular," AC 90-45, DOT, Federal Aviation Administration, August 18, 1969.

21. Anonymous, "Air Traffic Control Service for Area Navigation Equipped Aircraft Operating in the United States National Airspace System," Handbook 7110.18, DOT, Federal Aviation Administration, February 27, 1970.

22. MacKenzie, F.D. and Haroules, "Preliminary Results of Loran-C Flight Testing in the State of Vermont, "U.S. Department of Transportation Research and Special Programs Administration Transportation Systems Center, Report #DOT-TSC-RSPA-80-21, November 1980.

TE

ED

82